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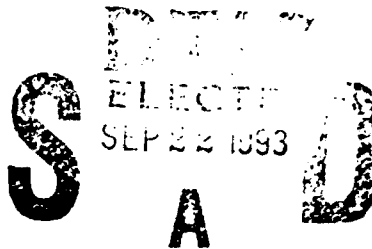


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**ELECTRONIC MANUFACTURING PROCESS IMPROVEMENT  
(EMPI) FOR AUTOMATIC WINDING OF QUADRUPOLE FIBER OPTIC  
GYRO SENSOR COILS**

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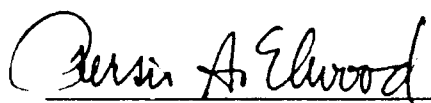


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## **SYMBOLS, ABBREVIATIONS, AND ACRONYMS**

EMPI	Electronic Manufacturing Process Improvement
ACWS	Automatic Coil Winding Station
FOG	Fiber Optic Gyro
TQM	Total Quality Management
QFD	Quality Function Deployment
SPC	Statistical Process Control
VRP	Variability Reduction Program
$C_p$	Process Capability Index
$C_{pk}$	Process Performance Index
PGA	Payguide Assembly
HBA	Holding Bracket Assembly
cw	Clockwise
ccw	Counterclockwise
IMU	Inertial Measurement Unit
PCWS	Prototype Coil Winder Station
INU	Inertial Navigation Unit
DOE	Design of Experiment
rpm	Revolutions per Minute
CIM	Computer Integrated Manufacturing
SLC	Salt Lake City
OD	Outside Diameter

## **SECTION 1**

### **SUMMARY**

The object of the Electronics Manufacturing Process Improvement (EMPI) Automatic Coil Winding Station (ACWS) program was to improve the Automated Coil Winding Station design and winding process through the application and implementation of statistical techniques. Benefits to the Air Force will be demonstrated through improved product reliability, improved process controls, reduced product costs, and/or reduced cycle time. Specific objectives are a reduction in operator time from 24 hours to 4 minutes and improvement in process yield from 80 percent to 98 percent. Automation and optimization focused on the unique quadrupole coil requirements by winding equally one-half of one sensor coils' worth of fiber onto two separate transfer spools; then winding the fiber from these two transfer spools onto the gyro sensor spool.

The program was separated into four phases:

1. Process Definition
2. Critical Factor Identification
3. Variability Reduction
4. Statistical Process Control (SPC) Implementation

A major aspect of this program was indoctrination of all participating disciplines in the complex mechanics of quadrupole winding. Important as the optical benefits are from a quadrupole wind so, too, are the complex mechanical implications in successfully achieving it reliably, at low cost.

Quadrupole wind is the physical placement or winding of optical fiber onto the sensor spool starting from the midpoint of the fiber and winding it in such a manner that segments of fiber, equidistant from the midpoint of the fiber are beside or nearly beside each other. Except for the first and last layers, the layers are wound in pairs first using one of the two strands originating at the midpoint to wind a double layer, and then the other strand to wind the next double layer. The strands must be wound in opposite directions, i.e., clockwise (cw) and counterclockwise (ccw), for the interferometer to be able to sense angular rotation.

Earlier use of the Litton designed manual and prototype winder stations identified many of these complex implications. With certain fundamentals basic to quadrupole winding regardless of some features such as spool size, etc., a well identified process definition and/or flow with the support of a QFD Matrix also clearly identified certain priorities. Among these was the importance of making the station extremely versatile through computer and software control. However, despite this versatility, critical factors analysis indicated that the fiber guide and its control were central to the

success of the ACWS. When a reliable fiber guide was achieved, it was possible to exercise variability reduction through computer software control.

Eventually, when the station could deliver consistent performance, given no change in software parameters, it was then possible to introduce and optimize variables such as speed, tension, fiber gap, guide position, etc. Through use of a Taguchi L9 array it was possible to identify fiber gap as the strongest factor in controlling fiber crossover: a decidedly important and crucial element in gyro optical performance. However, it was impossible to control fiber gap until the complex issues of the fiber guide assembly were perfected. This was achieved through DOE effort on the prototype coil winding machine via a number of iterative designs embracing how to keep the fiber captive in the guide using means not stressful or abrasive to the fiber.

The ACWS was released to production use when 25 coils made up the first SPC database. The following five parameters are currently being monitored as criteria for acceptance:

1. Auto wind fiber length
2. Cross coupling at 25°C
3. Loss at 25°C
4. Max loss from -55°C to 10°C
5. Max cross coupling

Of these five parameters, the first four parameters show 100 percent parts acceptance. However, the last parameter indicates 1.43 percent out-of-spec at the upper end. From this small sample of 25 parts, it is apparent that all five parameters suggest that an investigation of these profiles could lead toward some reduction in cost. The first four by some relaxation in tolerances perhaps, and the latter by determining how to shift the  $C_{pk}$  upper end  $3\sigma$  limit so that the product rejection is 0 percent. Nonetheless, these product capability indices clearly identified that some possible action is in order.

Also note that the actual rejection is higher than that indicated by the indices. This disparity may be attributed to the small sampling of 25 parts which have not yet filled in the normal Gaussian distribution.

Program benefits from the ACWS are already being realized:

1. Coil winding cycle time has been reduced from 24 hours on the manual station to 1.5 hours on the ACWS
2. Labor time has been reduced from 32 hours on the manual station to 0.3 hour on the ACWS

3. Better process controls have improved performance and yield
4. Lower skill labor is required

It should also be noted that subsequent preliminary data already show that the coil winding cycle time is approaching one hour with further reduction anticipated as the operators become more familiar with the broad versatility of the ACWS. All these factors bode well for the Air Force benefits. For instance, extrapolating into future sales of an estimated 3,000 systems (9,000 gyros), this could contribute toward a potential savings to the Air Force over the next 5 or 6 years of approximately \$30,000,000. Then there are additional savings that could be realized from other manufacturers utilizing the knowledge gained from the ACWS.

## **SECTION 2**

### **INTRODUCTION**

#### **REPORT ORGANIZATION**

The final report is composed of eight sections:

- Section 1: Provides a summary of the results completed during the term of the Electronic Manufacturing Process Improvement (EMPI) contract.
- Section 2: Introduction to the final report and Litton's approach to the EMPI program for the automatic coil winder station (ACWS).
- Section 3: Quadrupole Winding and ACWS Concept
- Section 4: Phase I: Process Definition
- Section 5: Phase II: Critical Factor Identification
- Section 6: Phase III: Variability Reduction
- Section 7: Phase IV: SPC Implementation
- Section 8: Lessons learned resulting from experience gained from winding optical fiber.

#### **2.1 Program Objective**

Litton's objective in performing the EMPI program was to improve the ACWS design and winding process through the application and implementation of statistical techniques. Figure 2-1 shows the resultant Automatic Coil Winding Station (ACWS). Starting from the left of the photograph on a granite block and mostly black, is the winder mechanism, robotics, etc. The tall console in the center is the electronics and associated power supplies, servo controllers, etc. To the far right is the computer, monitor, etc. This system is fully automatic and computer controlled for maximum versatility in not only winding essentially most any size fiber spool but also for performing other variability exercises and SPC activities. Benefits to the U.S. Air Force will be realized through:

- a. Improved product reliability
- b. Improved process controls

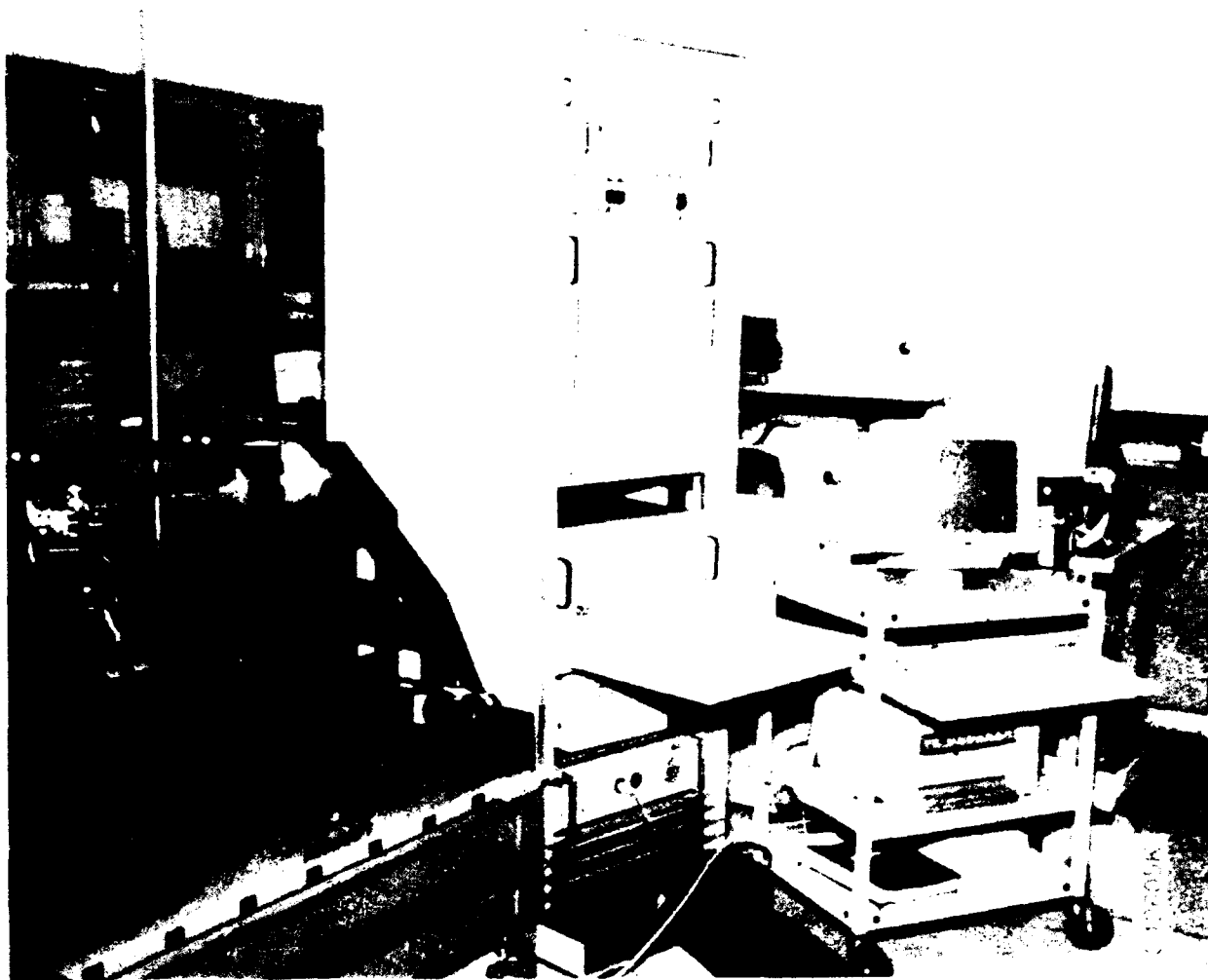


Figure 2-1. Automatic Coil Winding Station (ACWS)

c. Reduced product costs

d. Reduced cycle time

The resulting ACWS process and hardware will directly benefit Litton in the fabrication of fiber optic gyro (FOG) navigation systems. In addition, because of the government-industry ACWS technical debriefing and tour, the methodology and design improvement of the ACWS will be offered to other industries having coil winding applications and requirements.

A cost benefit analysis for the ACWS was done early in the program to understand manufacturing cost vs early automation. Justification for the effort was based on 1) attainment of low-cost potential of FOGs highly dependent on automation of manufacturing processes, 2) cumulative savings potential to the government with early automation of FOG factory  $\geq$  \$50M in the first six years based on Litton's market share, and 3) technology transfer to sensor manufacturing community will multiply payback to government. A savings of \$11,000,000 was projected for automation of the coil winding part of manufacturing missile IMU's for all services in the first six years of production.

## **2.2 Scope: Variability Reduction Program Overview**

The EMPI program is a Variability Reduction Program (VRP) consisting of four basic phases:

### **Phase I – Process definition**

- Identify major process steps
- Breakdown major steps into micro steps
- Assign process and labor times to each step

### **Phase II – Critical Factor Identification**

- Bring prototype coil winder on line
- Wind three coils in succession
- Perform optical test on coils:
  - Insertion loss, polarization holding and coil transit time
- Baseline prototype coil winder present performance
- Benchmark prototype coil winder performance and capability with respect to manual coil winder

### Phase III – Variability Reduction

- Optimize critical coil winding process factors
- Experimentation using Taguchi methods
- Establish controllable coil winding process factors
- Process capability study
- Confirm optimized settings through experimentation
- Wind successive coils and analyze results to determine control methods' effectiveness
- Calculate  $C_p$  and  $C_{pk}$  indices to determine spread and distribution location

### Phase IV – Proof Process in Production Environment

- Start production coil winding
- Implement control methods
- Apply SPC to identify/minimize external influences to coil winding process
- Use control charts, cause and effect diagrams, etc.
- Perform process capability study and calculate  $C_p$  and  $C_{pk}$  indices

The first phase of Variability Reduction basically defined the processes. Phase II brought the prototype winder on-line and initiated the beginning of Taguchi DOE methods in addition to classical DOE methods. Figure 2-2 outlines these basic stages of the experiment design. Information gained from Phase II was used by the process operators to monitor the critical characteristics as the opening for Phase III. Cause-and-effect analysis was performed as necessary thus establishing and maintaining process control. This is a continuous effort, as indicated in Figure 2-3, followed by another continuous cycle, Phase IV, where process variables will be under SPC with  $C_p$  and  $C_{pk}$  indices being continuously monitored for improvement progress.

A Quality Function Deployment (QFD) matrix was developed as part of Phase I and utilized to ensure that the factory (Liton, Salt Lake City) customer requirements are incorporated into the ACWS design, mainly coil design requirements, and manufacturing requirements.

The program included all interstation variables, i.e., process variables that are controlled outside of the ACWS workstation, but may still contribute directly to the workstation yield. Examples of interstation variables are optical fiber tensile strength and smoothness of the coil spool hub (or mandrel).

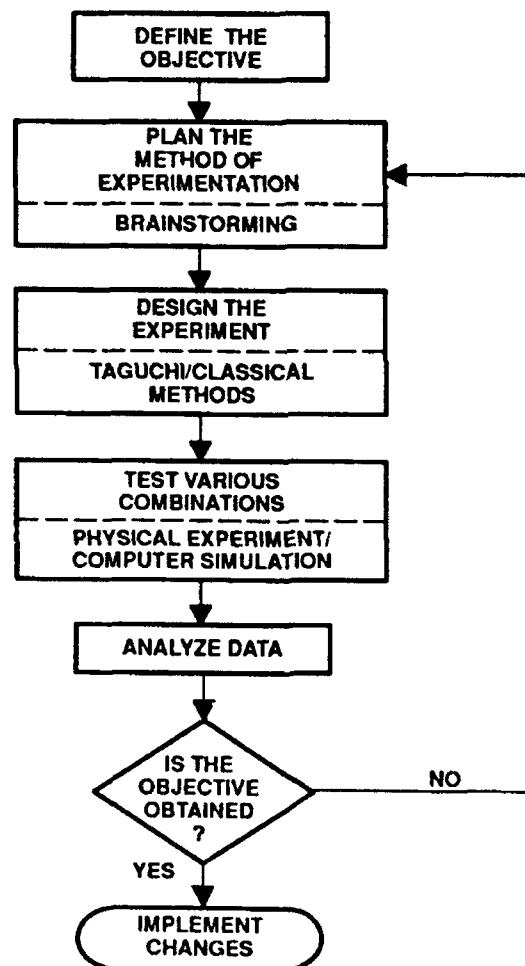


Figure 2-2. Stages of Experiment Design



## SECTION 3

### QUADRUPOLE WINDING

This section of the report addresses two important aspects of the ACWS: 1) what is Quadrupole wind, and 2) operational concept in achieving it.

#### QUADRUPOLE WIND

A thorough knowledge of the manner in which the fiber optic coil is wound by Litton is needed to best understand the methods and procedures utilized in the design of the ACWS. One can easily relate to the manner in which sewing thread is wound onto a spool – one end of essentially endless source of single thread is taken from a single transfer spool and is layered down adjacent to the last wind or turn until it reaches the end of the spool (see Figure 3-1); then repeating subsequent layers, back and forth, until the spool is full. Litton's fiber optic spool utilizes an unfamiliar process known in the industry as quadrupole wind.

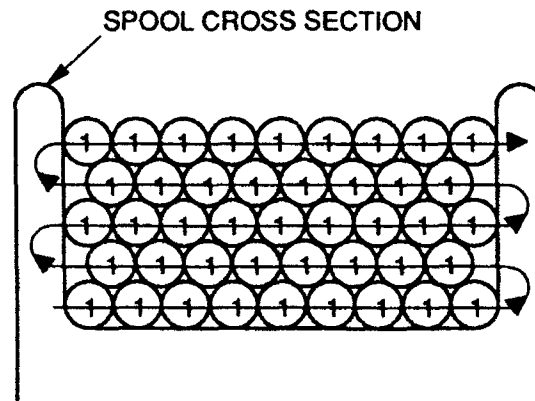


Figure 3-1. Thread Winding Sensor Coil

The quadrupole fiber winding process or technique is key to achieving adequate bias stability performance over rapid thermal ramp and high vibration environments expected for the Air Force FOG IMU. This process must also produce a coil with low loss to achieve the random walk goals and with low polarization cross-coupling to achieve the day-to-day and long-term bias stability goals. Through internal development efforts (IRAD) Litton has successfully developed a fiber winding process which provides excellent performance. The most important elements of Litton's coil winding process is the quadrupole wind pattern.

The basic principle of the quadrupole winding technique is to render the environment symmetrical about the midpoint of the fiber on the coil as shown schematically in Figure 3-2. The process steps for winding a quadrupole sensor coil are shown in Figure 3-3. The fiber is prewound onto two transfer spools. The midpoint of the fiber is placed on the coil form and the first layer of coil is wound using one of the supply spools (see Figure 3-3b). Next, the second and third layers are wound from the second supply spool (Figure 3-3c). The fourth and fifth layers are wound from the first spool, Figure 3-3d, etc. In this manner, fiber equidistant from the coil midpoint is collocated on the fiber coil. This reduces the sensitivity to environmental effects by 10—1000X. Performance typical of Litton quadrupole wound coils is shown in Figure 3-4.

### 3.1 Operational Concept

The concept for implementing the quadrupole wind requirements in an automated machine is reviewed. An isometric view of the winding device will be used to visually walk through and facilitate that explanation. Photos of the ACWS hardware are included for additional clarification.

Figure 3-5 is the basic coil winding mechanism. The console, computer, and monitor that control and drive the winding mechanism are not included in this drawing. The photograph of the ACWS motion control platform is shown in Figure 3-6.

Referring to Figure 3-5, two payguide assemblies (PGA) are initially coupled to their respective holding bracket, using a spring-loaded latch mechanism located on the holding bracket. The payguide assemblies hold the transfer spools, payout fiber, and guide the fiber to the appropriate point on the spool being wound. A full transfer spool of fiber is mounted onto each payguide assembly (PGA), e.g., one transfer spool on PGA no. 1, while transfer spool no. 2 is mounted onto PGA no. 2. Each has 1/2 the total gyro fiber length requirement from a previous build transfer operation. A typical step-by-step operation follows:

- a. Coupler robot (x, y, Z) moves beneath a PGA no. 1, couples and removes the PGA from holding bracket assembly (HBA) no. 1. See Figure 3-7. During removal immediately following coupling, a tension servo is engaged to eliminate slack in the fiber during motion. The robot moves PGA no. 1 to the inner flange of the sensor spool in preparation for the first layer of fiber. Sensor motors 1 and 2 are contoured with x to achieve a thread wind. PGA no. 1 is then parked on HBA no. 2. During the laying down of the first layer of fiber, PGA no. 2 rides passively on HBA no. 1 (out of the critical work envelope) with no net payout from PGA no. 2 onto the sensing spool.
- b. The second and third layers of fiber are next applied to the sensor spool using PGA no. 2 and following the above steps in a.
- c. Layers 4 and 5 are next applied to the sensor spool using PGA no. 1 and following the steps in a. again. These steps continue until the coil is completely wound.

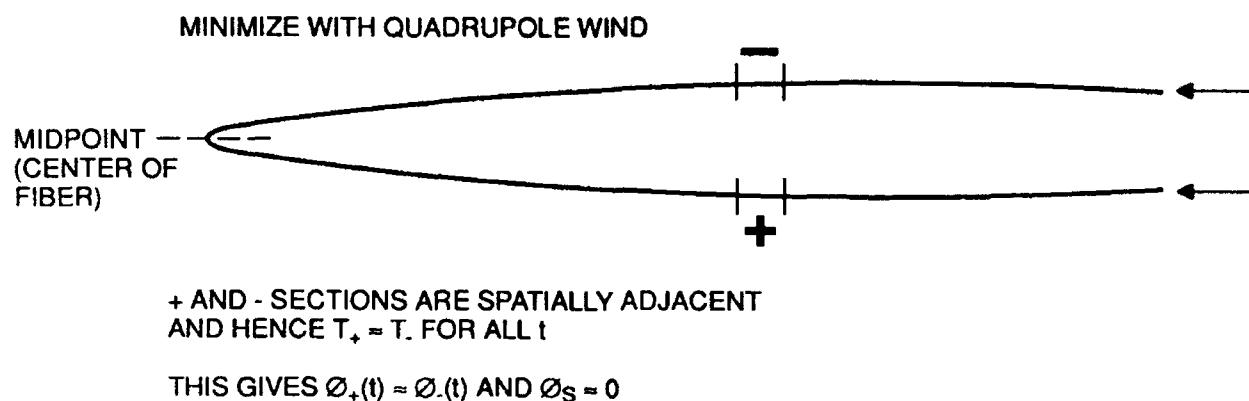


Figure 3-2. Shupe Effect

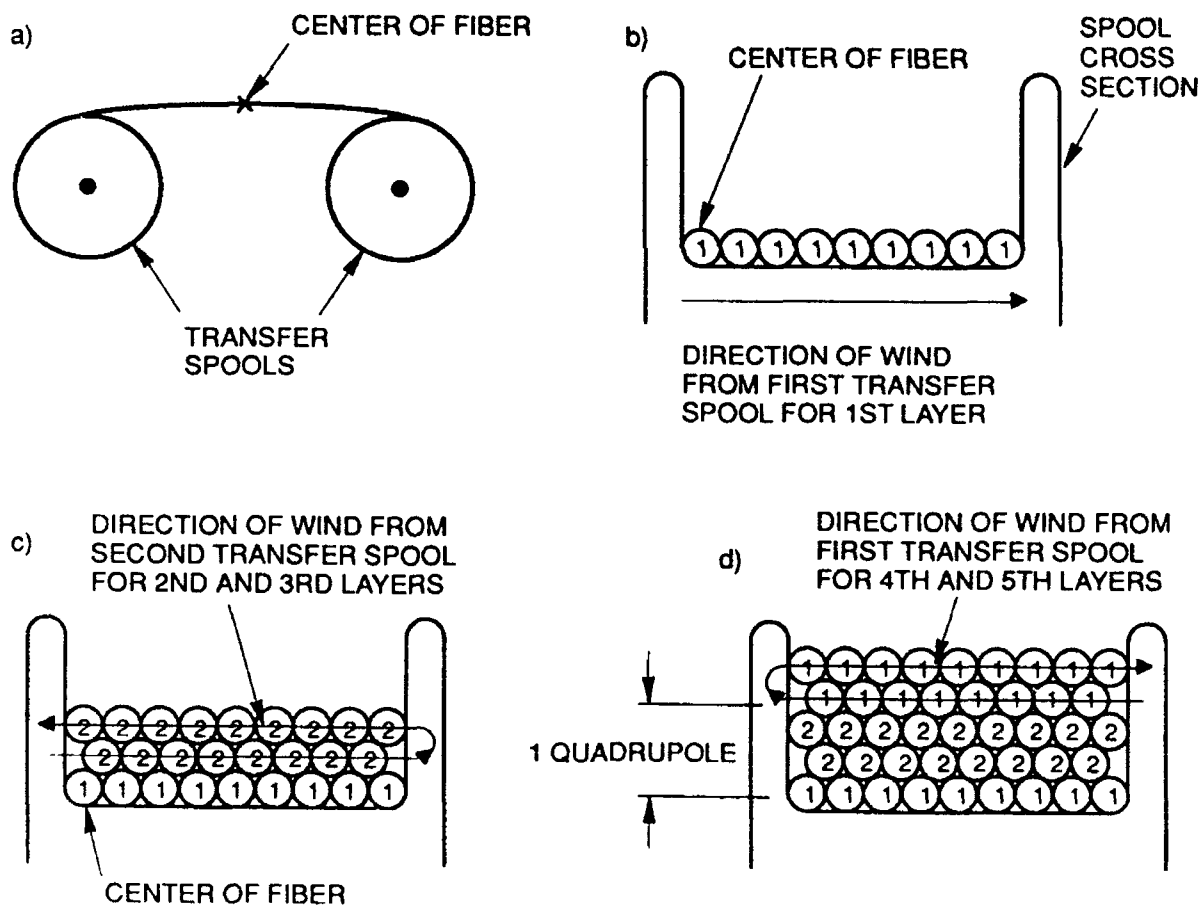


Figure 3-3. Steps In Winding Quadrupole Sensor Coil

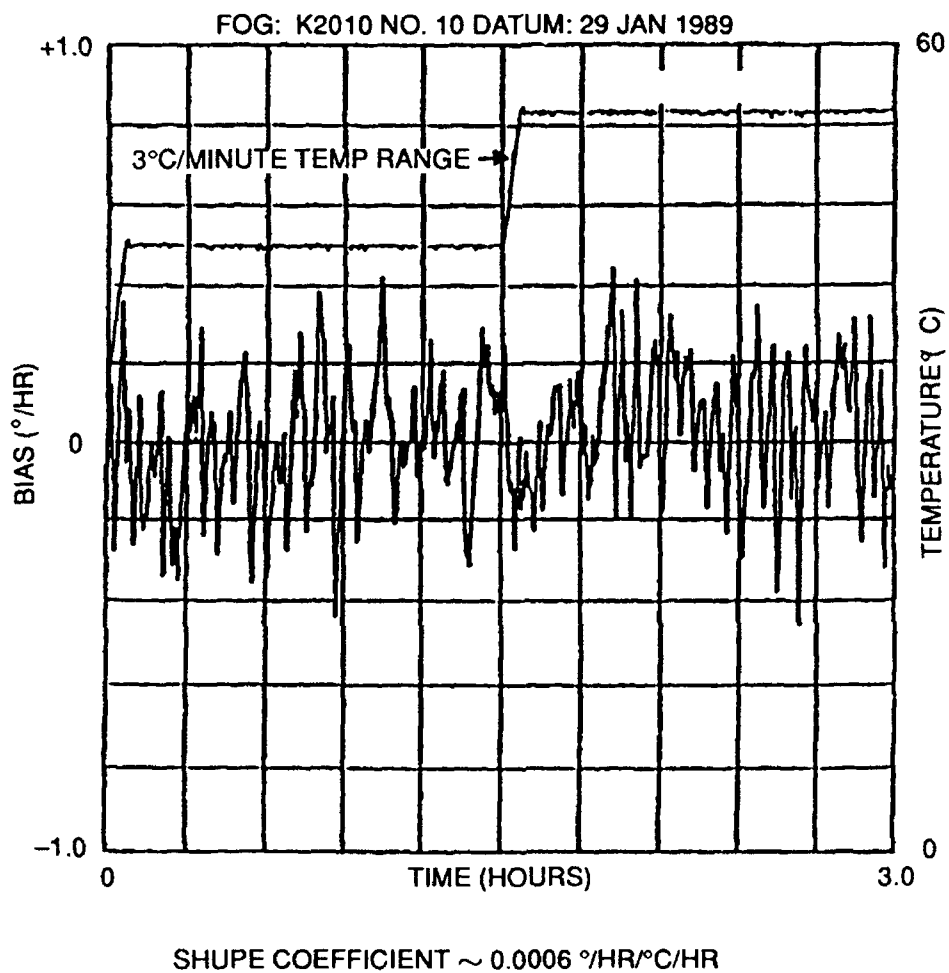


Figure 3-4. Quadrupole Coll Wind and Resulting Thermal Shupe Effect

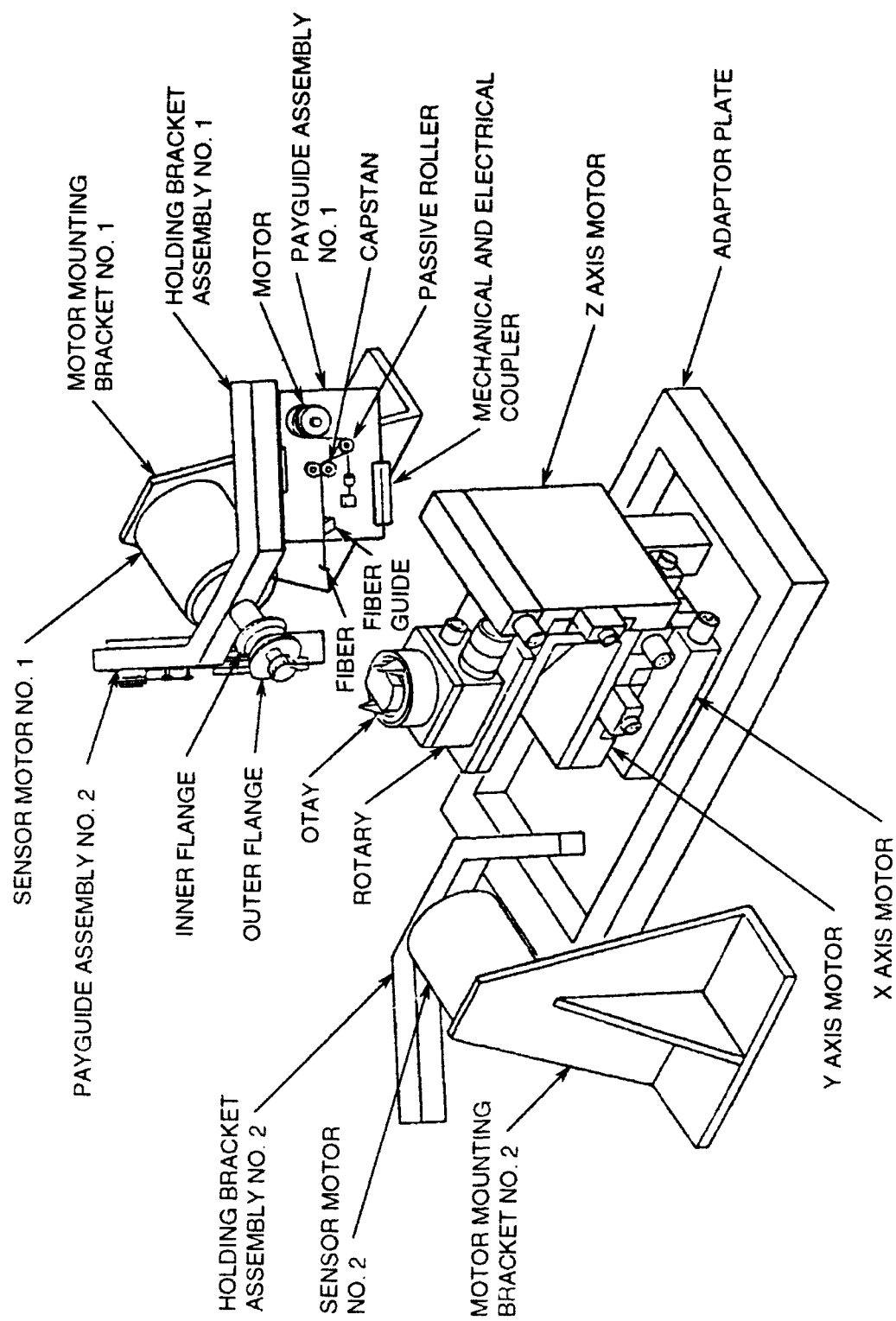
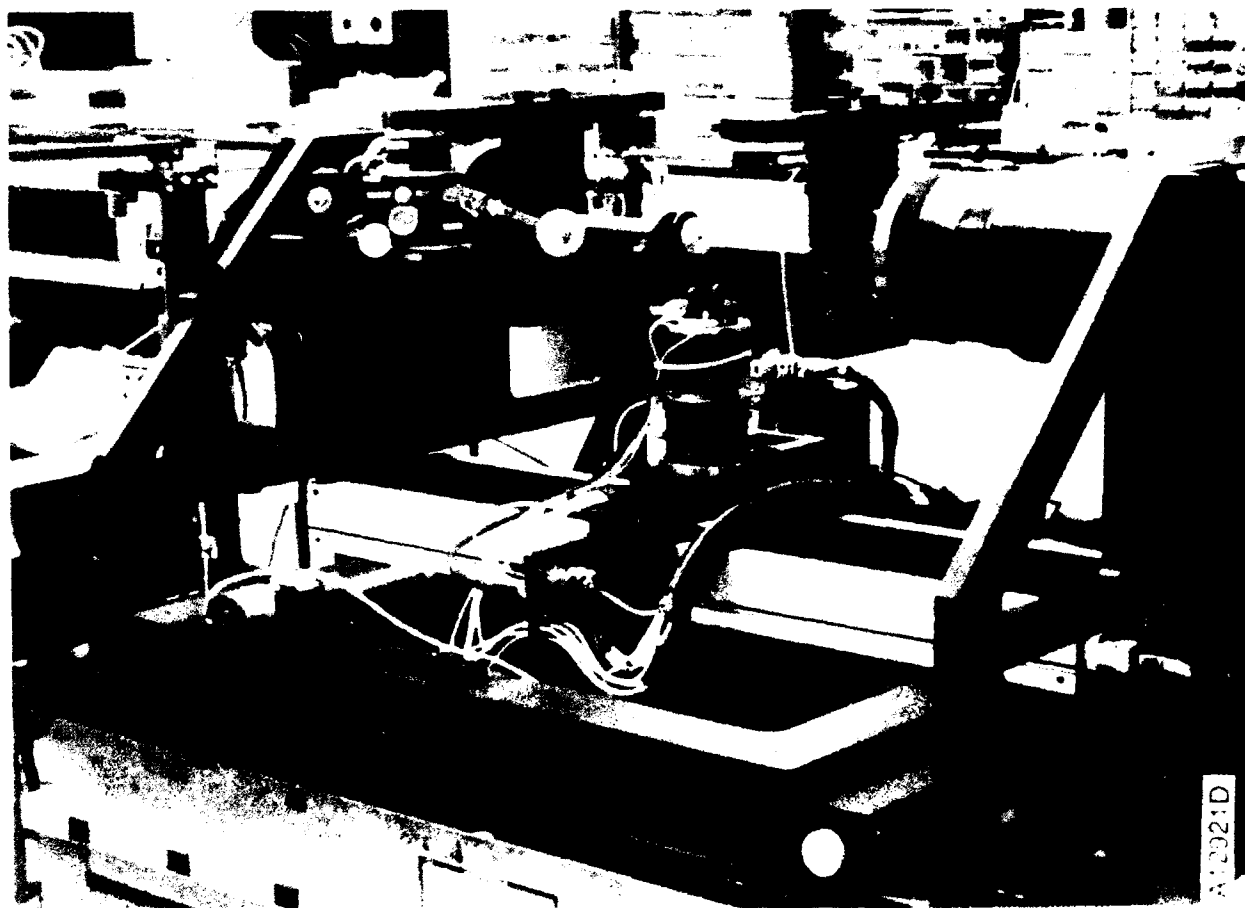
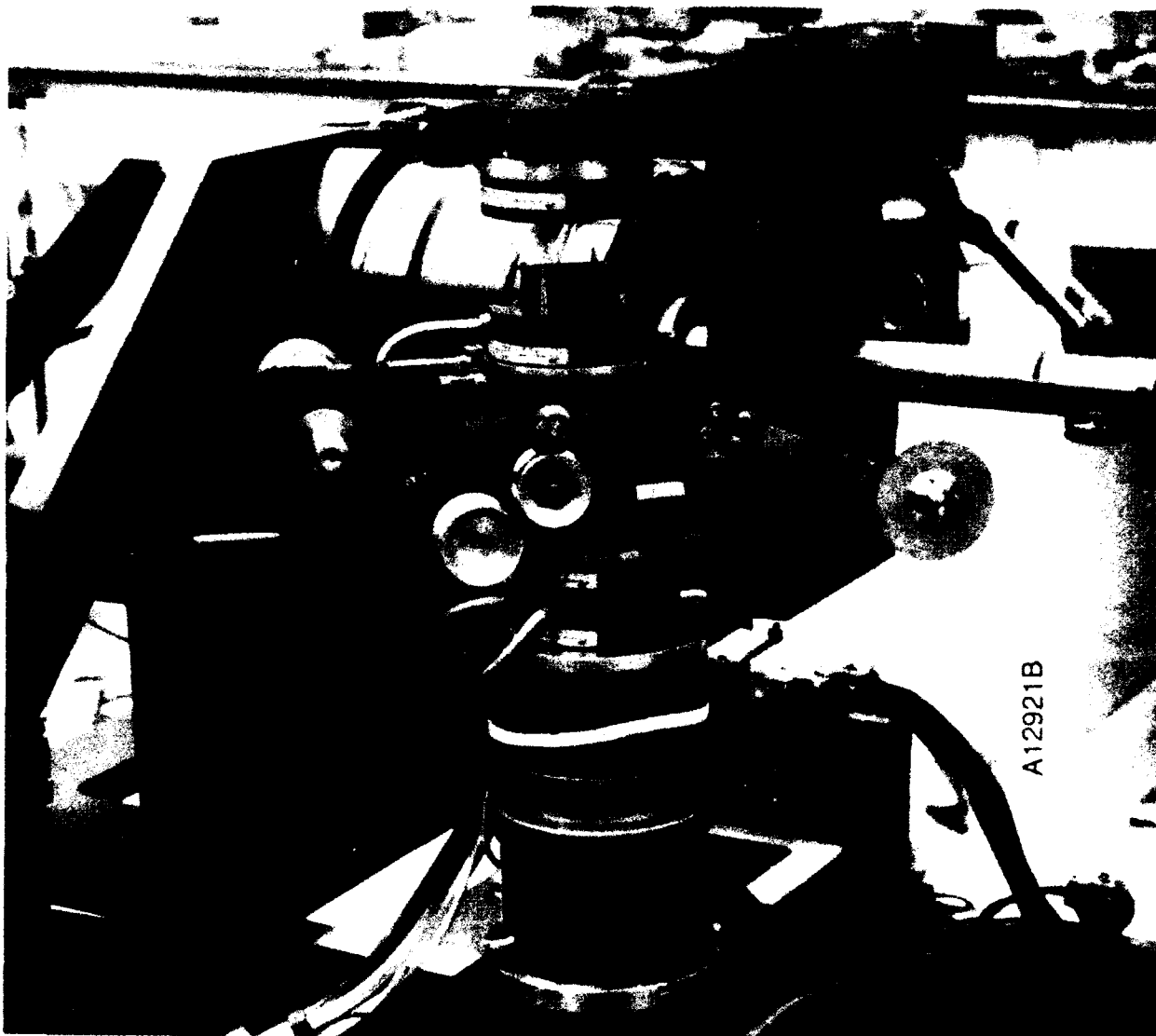


Figure 3-5. Isometric Diagram of the Basic ACWS Mechanism



**Figure 3-6. ACWS Motion Control Platform**



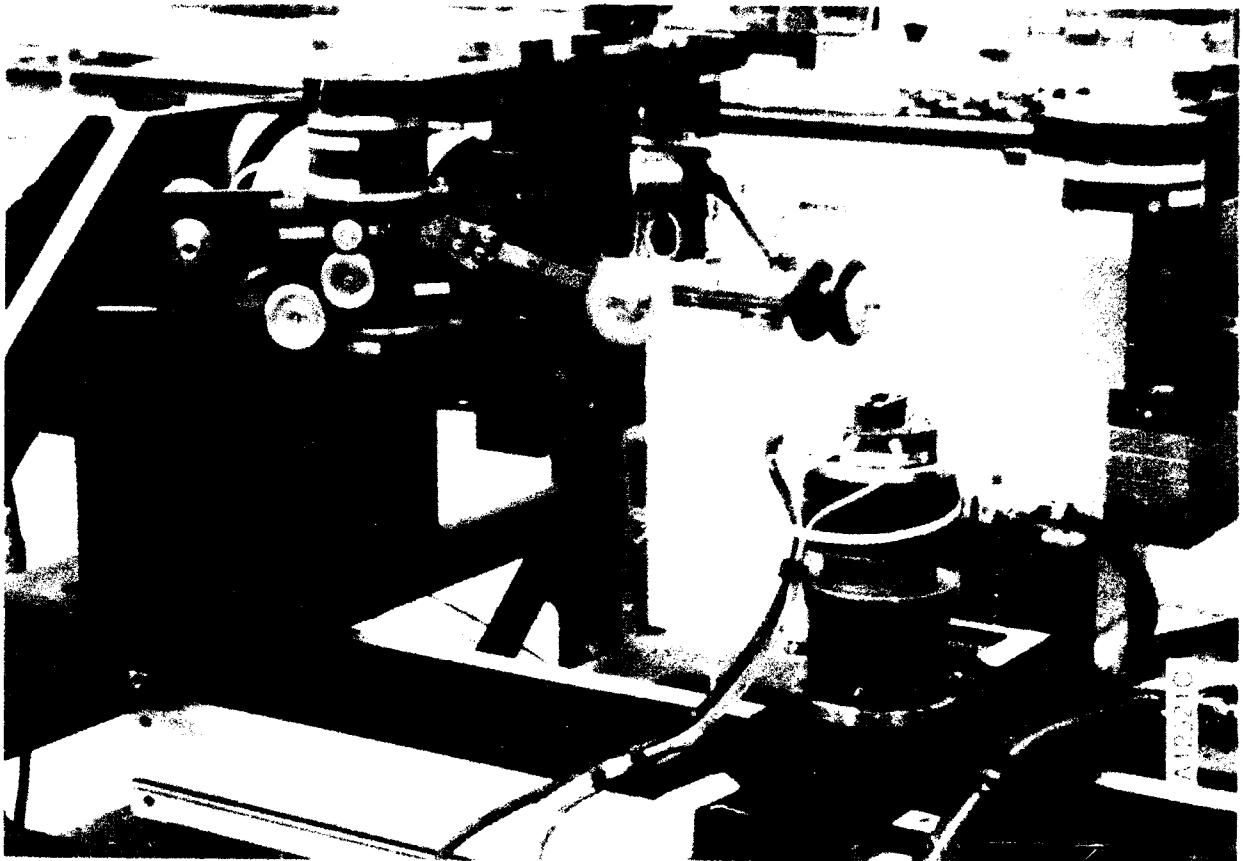
**Figure 3-7. ACWS Payguide Removed from Holding Bracket Assembly**

During the above steps, when the PGA is passively held on the HBA, tension is maintained on the fiber by a spring-loaded capturing mechanism extending from the PGA mounting plate outwards to capture the dancer arm. The arm will not flop around while riding on the HBA even in the absence of electrical power and servo control.

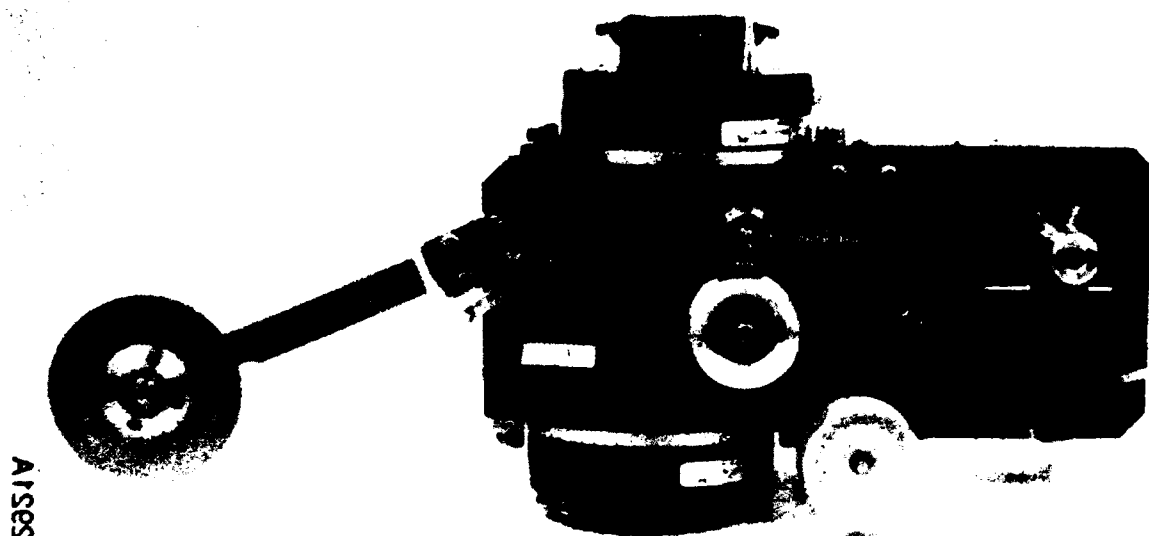
The production ACWS has two payguide assemblies coupled with a 4-axis robot that are automatically removed from their respective holding bracket when needed within the winding sequence (Figures 3-8 and 3-9). A servo loop implemented between the transfer spool and in conjunction with a dancer provides tension control during winding. The dancer is captivated when not in use using a normally retracted (spring loaded) activator. A precision encoder wheel is used to monitor the length of spent fiber. The fiber guide allows precision control of fiber application within the flanges of the sensor spool. The combination of a long fiber guide with a very thin profile to place the fiber at the right depth and also into the narrow gap up near the flange required a very rigid guide material. The transfer spool motors are geared to improve servo performance (at low speeds) and to reduce undesired rotation which would result in tension variations when the servo is disabled. The precision encoder wheel allows precise length measurement of all cw and ccw turns using the formula:

$$L = \pi d (\text{turns})$$

It should be noted that this operational concept offers considerable flexibility in accommodating variability reduction programs (VRD), because the basic mechanism is all automatic and driven by computer controls. Only minor changes to the payguide assembly (PGA) wheel may prove necessary to tailor it toward other certain specific size fibers.



**Figure 3-8. ACWS Payguides Parked In Holding Bracket**



ATSCSIA

**Figure 3-9. ACWS Paygulde Assembly (PGA)**

## **SECTION 4**

### **PHASE I – PROCESS DEFINITION**

Phase I was organized into the following activities as part of the process definition for an Automatic Coil Winding Station (ACWS):

- Develop the microprocess flow
- Identify areas of cost concern
- Scrap concern
- Design analysis
  - Review the coil design for the ACWS
  - Identify critical coil characteristics
- Document customer requirements (QFD)
- Optimize operations for the Prototype Coil Winder Station (PCWS)

#### **DEVELOPMENT OF THE MICROPROCESS FLOW**

The build and test flow of a fiber optic gyro (FOG) Inertial Measurement Unit (IMU) is illustrated in Figure 4-1. The coil winding activity, enclosed by the dotted line rectangle, is one of 10 optical component activities (plus electronics) required for assembly. Each IMU consists of three gyros, each gyro requiring a fiber optic sensor coil, for a total of three fiber optic sensor coils for each IMU.

#### **4.1 Coil Winding Macro- and Microflows**

Coil winding macro- and microflows are developed from the following activities:

- Identify major process steps
- Break down steps into microsteps
- Assign process and labor times to each step.

Winding a fiber optic coil consists of two winds: 1) the transfer wind or removal of fiber from the vendor shipping reel to two transfer spools, and 2) the quadrupole wind or winding the fiber from the transfer spools to the gyro sensor coil spool (refer to Figure 4-2a). Additionally, a 9-step micro-flow for the transfer was prepared. Referring to Figure 4-2b, the calculated touch labor for a 200m

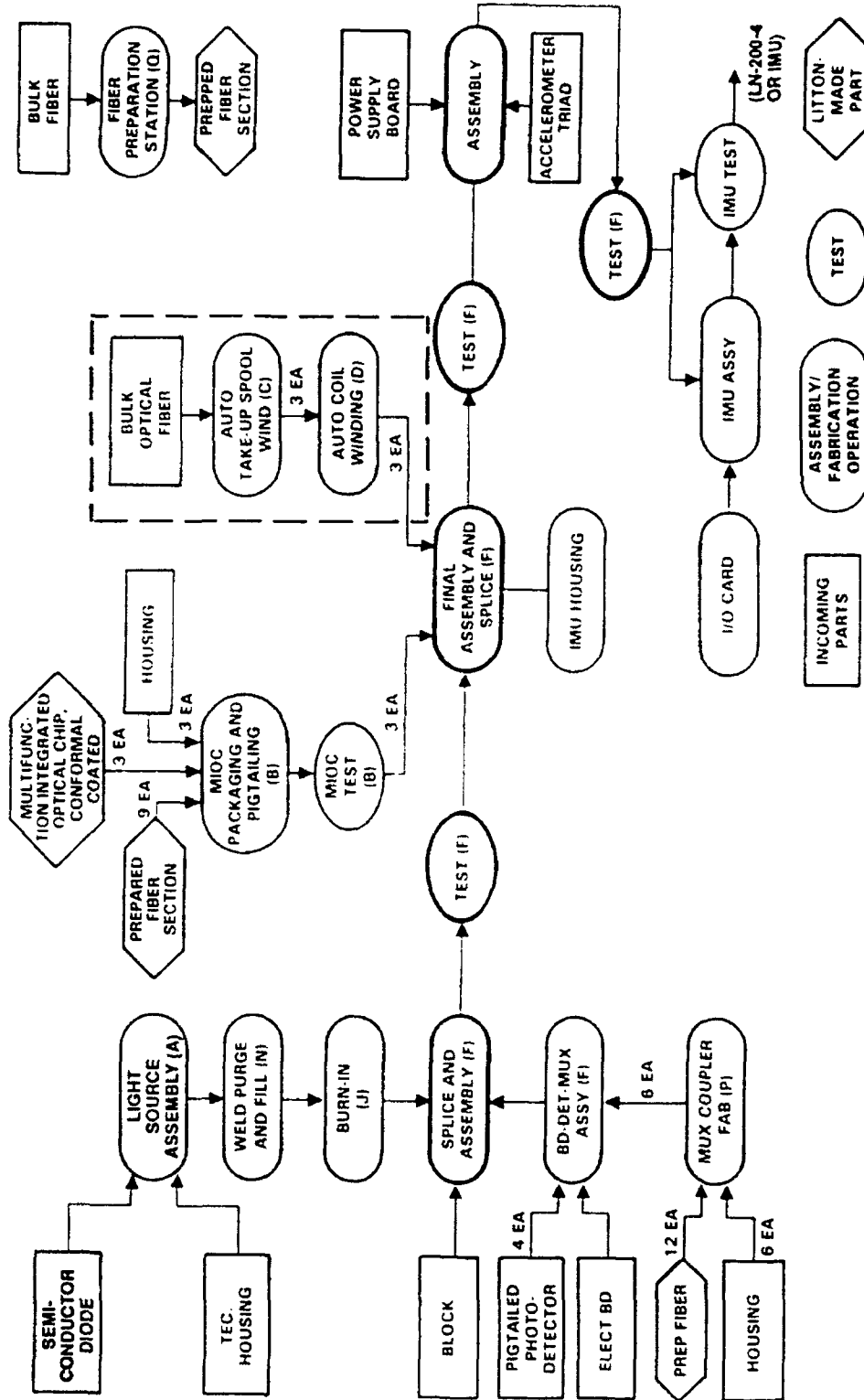
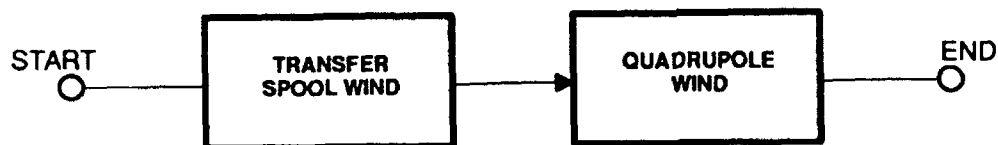
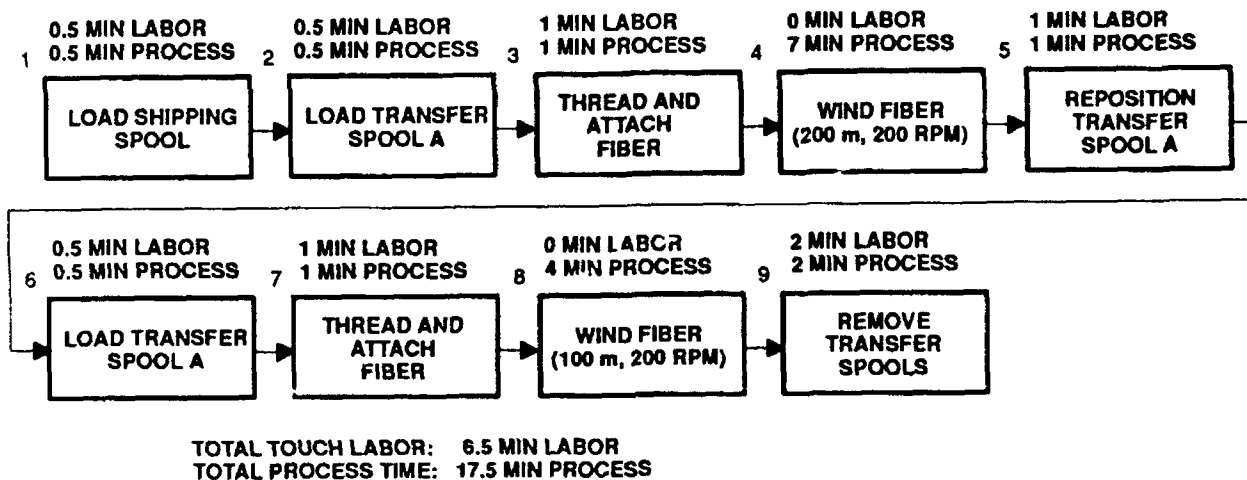


Figure 4-1. Fiber Optic Gyro Build/Test flow for Factory



**a. Coil Wind Macroflow**



**b. Transfer Wind Microflow**

**Figure 4-2. Fiber Optic Coil Wind Macro- and Microflow**

transfer wind is 6.5 minutes and the total process time is 17.5 minutes. Following preparation of the transfer wind microflow, the ACWS quadrupole wind microflow was broken down and prepared step-by-step the same way. Refer to Figure 4-3a and b, the calculated touch labor time for a 200m quadrupole wind is 10 minutes and the total process time is 59.2 minutes.

#### 4.2 Areas of Cost Concern

Work was then directed toward identifying areas of cost concern.

Evaluation of process/subprocess steps for the following:

- Operator time
- Station throughput
- Potential for scrap.

**4.2.1 Operator's Time.** For operator's time, the projected touch labor is 16.5 min, i.e., the sum of 6.5 minutes for the transfer wind and 10 minutes for the quadrupole wind (for a 200m coil). The touch labor goal is four minutes. The approach used to meet the goal was to optimize the ACWS/ operator interface with the following:

- User friendly software
- Simplified spool mounting
- Simplified fiber threading
- Simplified and/or automated final fiber attachment.

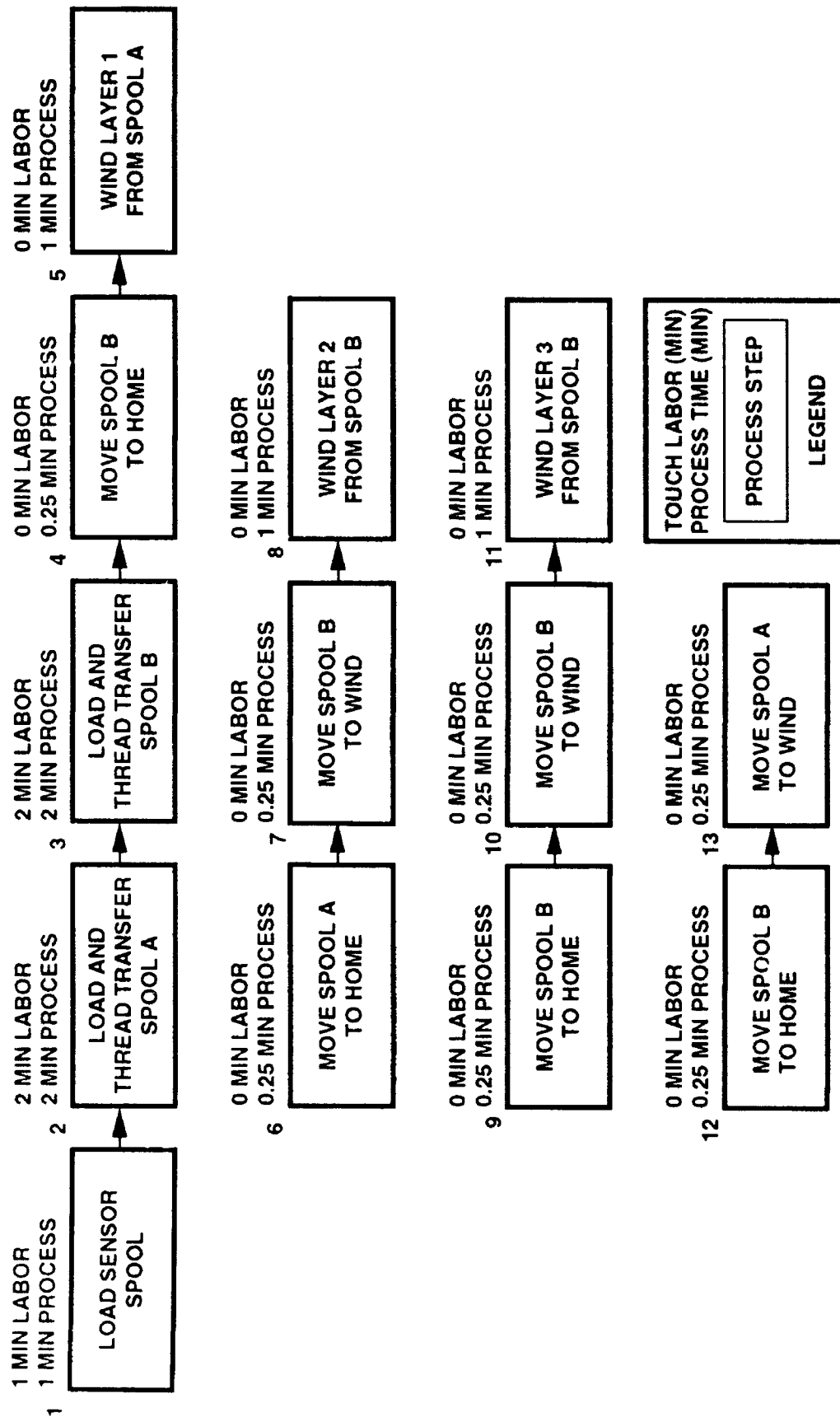
**4.2.2 Station Throughput.** To address ACWS throughput, a tradeoff study was performed to determine the efficacy of using a dedicated transfer wind station versus performing both transfer and quadrupole winds on the ACWS. For the study, the following parameters were considered:

- Recurring cost of transfer wind station and quadrupole wind station
- Throughput of each station
- Production rates
- Learning curves
- Projected coil and system yields.

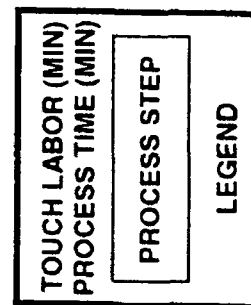
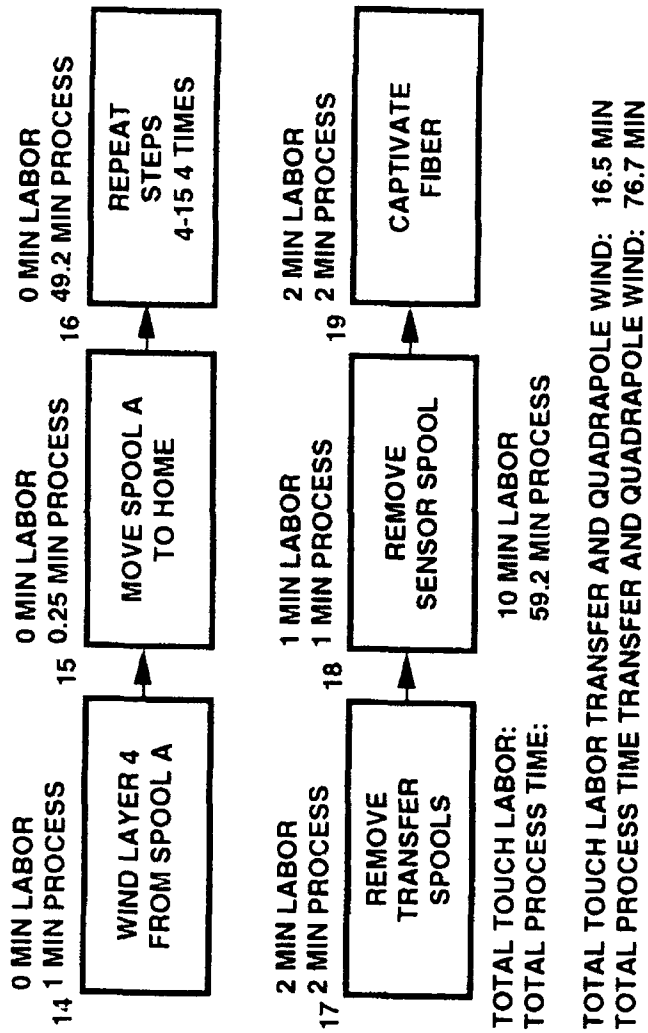
From the study, it was concluded that if 25 or more systems (75 coils) are fabricated per month, the equipment cost is lower using a dedicated transfer wind station for the transfer wind. The unacceptable alternative is to have two ACWS'. Refer to Figure 4-4 for the results of this cost analysis.

**4.2.3 Potential for Scrap.** The area of scrap costs received considerable attention. The following factors were implemented in the ACWS to reduce/hold costs:

- On-line coil length measurement to minimize excess fiber usage
- Closed-loop tension control
- Large diameter pulleys and capstans (> 1 inch diameter) to minimize fiber stress (less bending)
- Design operator interface to minimize potential for snagging, stressing, or breaking fiber during handling to minimize loss of coils
- Minimum fiber/fiber crossovers so coils meet performance.



a. Automated Quadrupole Wind Microflow  
Figure 4-3



b. Automated Quadrupole Wind Microflow (cont)

Figure 4-3 (cont)

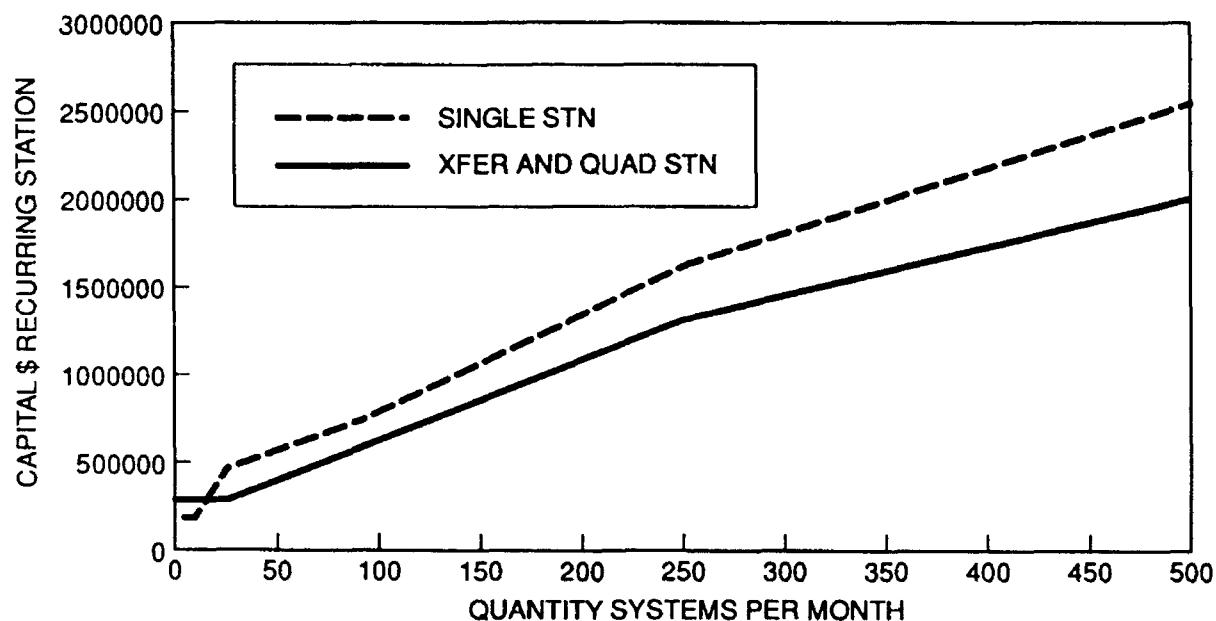


Figure 4-4. Coll Winder Station Cost Analysis

### 4.3 QUALITY FUNCTION DEPLOYMENT (QFD)

It was important at the outset of the program to ensure that the customer (USAF, contractors, factory, etc.), requirements were incorporated into the ACWS design and that the critical design features were identified. To effect this, an initial QFD activity was organized into three areas:

- QFD ACWS design matrix goals
- QFD ACWS coil design requirements
- QFD ACWS manufacturing requirements.

**4.3.1 QFD ACWS Design Matrix Goals.** These goals were identified at the beginning of the program so that the ACWS design activity would be on track with a minimum of iterations. Refer to Figure 4-5.

Following the goals, work was then started on compiling the actual matrix, which consisted of a list of customer requirements and design features. Factory and reliability personnel were asked to provide requirements and design features; to weigh them accordingly; to identify the critical ones so that sight of their importance in the event of any necessary tradeoffs would not be lost; to feedback all problems as they developed; and finally, through this iterative process, to develop a matrix accordingly. See Figure 4-6 for a summary of the interactive process.

- TO ENSURE THAT FACTORY CUSTOMER REQUIREMENTS ARE INCORPORATED INTO THE COIL WINDER DESIGN
- TO IDENTIFY CRITICAL DESIGN FEATURES TO FOCUS DESIGN EFFORTS
- TO EVALUATE PROGRESS OF DESIGN BASED ON CUSTOMER REQUIREMENTS - IDENTIFY SHORTCOMINGS
- TO PROVIDE A FORUM OF COMMUNICATION BETWEEN THE SUPPLIER (DESIGNER) AND THE CUSTOMER (USER)

**Figure 4-5. QFD Coil Winder Design Matrix Goals**

- INPUT CUSTOMER REQUIREMENTS
- INPUT DESIGN FEATURES
- CORRELATE AND RATE STATION DESIGN FEATURES TO CUSTOMER REQUIREMENTS
- IDENTIFY CRITICAL DESIGN FEATURES - MAKE TRADEOFFS IF NECESSARY
- CUSTOMER RATES PROGRESS OF THE DESIGN IN TERMS OF HIS REQUIREMENTS
- PROBLEM AREAS ARE IDENTIFIED (IF ANY)
- FEEDBACK IS GIVEN TO STATION DESIGNER

**Figure 4-6. Compiling the QFD Matrix**

**4.3.2 QFD ACWS Coil Design Requirements.** Further, the QFD needed all the anticipated coil design requirement winding functions. This constituted not only information about the spool's physical characteristics both present and anticipated, but also the optical fiber, present and anticipated. This provided the basis for designing the station hardware and also for developing the menu-driven software. These are identified in Figure 4-7a. For more discussion on the optical requirements, see Appendix A.

**4.3.3 QFD ACWS Manufacturing Requirements.** Finally, to be complete, the QFD needed the manufacturing requirements. These items entailed not only production rate goals but other ergonomic factors. Such items as how the operator was to interface with the ACWS in the most efficient manner; what kind of a throughput was desired for optimum return on investment commensurate with yield and reliability; operator's actual touch time as well as total process time, and physical space of the ACWS commensurate with adequate safety requirements. And most important, their desire for considerable versatility in anticipation of future needs. These are summarized in Figure 4-7b.

**a. COIL DESIGN REQUIREMENTS**

- QUADRUPOLE WIND
- VERY LOW TENSION WIND
- ABILITY TO CONTROL AND VARY
  - FIBER/FIBER GAP (PITCH)
  - FIBER/FLANGE GAP
  - TENSION
  - WIND SPEED

**b. MANUFACTURING REQUIREMENTS**

- OPERATOR INTERFACE
  - COMPUTER/SOFTWARE
  - STATION LOADING/UNLOADING
- STATION THROUGHPUT
- OPERATOR TIME (TOUCH TIME)
- FACTORY CLM INTERFACE
- STATION FOOTPRINT
- SAFETY REQUIREMENTS
- ADAPTABLE TO VARIOUS COIL LENGTHS AND SPOOL DIMENSIONS

**Figure 4-7. Requirements for QFD Matrix**

The culmination of these three activities initiated in the QFD Matrix (see Figure 6-1). As a result of this matrix, the following preliminary assumptions were derived:

- Assumptions relative to critical areas of design were validated
  - Tension control
  - Motion control
  - Fiber breakage minimization
- Assumptions validated that customer requirements would be met
- Inputs were completed and work commenced on the analysis

The QFD Design Matrix will be revisited and discussed in more detail in Phase III of this report.

Through the QFD Matrix and feedback from FOG (Fiber Optic Gyro Engineering), Guidance Marketing, and Wright-Patterson, the preliminary specification was prepared with the intention of updating during the program. Refer to Table 4-1.

#### **4.4 LITTON PROTOTYPE COIL WINDER STATION (PCWS)**

Prior to the award of the ACWS contract, Litton G/CS had already developed a PCWS to support on-going engineering programs for the development of fiber optic gyro (FOG) inertial navigation units (INU). Since it played a significant role in the development of the ACWS, an understanding of this basic operation, though limited, is important. These are identified under Operation and Operating Instructions or input information.

##### **4.4.1 PCWS Operation.** Following is an operation overview of the PCWS

- The PCWS is a three-axis unit, including three tension sensors and is capable of winding coils in the Litton quadrupole configuration using Litton LN-200 Sensor spools
- All critical machine and spool geometric parameters are programmable from a 386-computer work station.
- For the quadrupole configuration wind, supply spool swapping (from supply position to ride position) is done manually. The PCWS cannot be modified to automate the spool swapping.

**TABLE 4-1. ACWS PRELIMINARY SPECIFICATIONS**

**Functional**

- Perform automated winding of fiber onto transfer spools from original bulk-packaged spool. This process is required prior to winding fiber onto the gyro spool
- Perform automated quadrupole winding of fiber from the transfer spools onto the gyro spool
- Control fiber tension during wind using closed-loop dancer mechanism
- Measure fiber length and cut fiber ends to specified length with tolerance of 1 percent
- Secure fiber ends of coil

**Station Time (200m coil): < 1 hour**

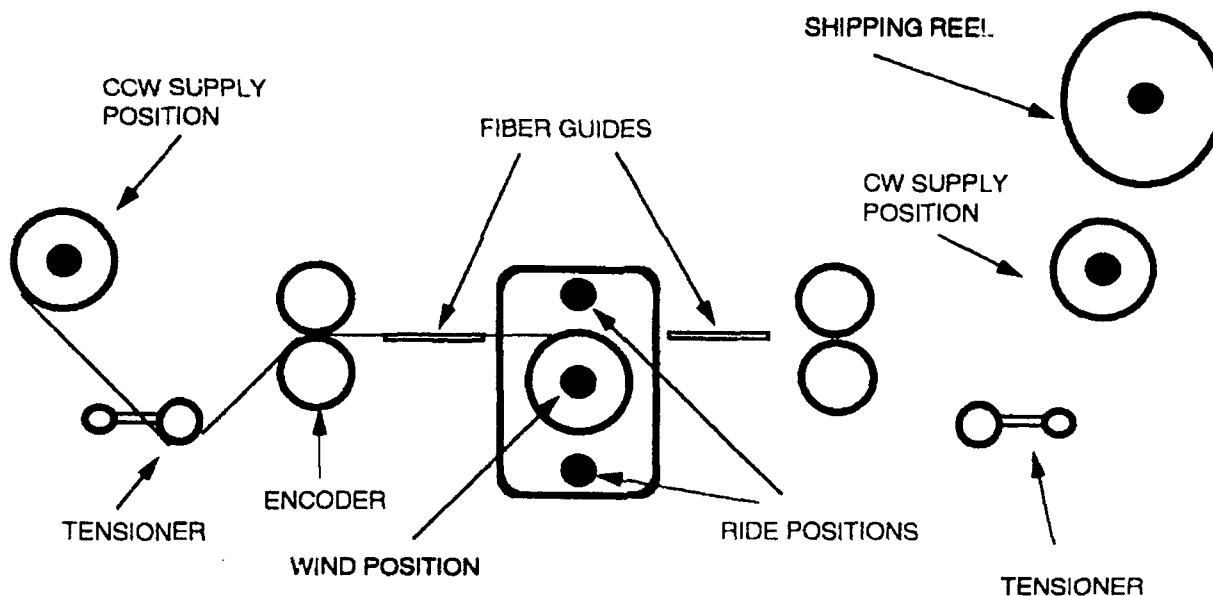
**Operator Time: < 4 minutes (present manual technique requires ~ 24 hours)**

**Yield: 98%**

**Parametric Versatility**

- Fiber diameter: 100 to 250 microns
- Sensor spool outer diameter: 2 to 10 centimeters
- Sensor spool internal widths: 0.5 to 8 centimeters
- Fiber lengths: 50 to 1000 meters
- Wind pattern: Quadrupole or thread
- Fiber tension: 2 to 20 grams

- To wind LN-200 coils, 220m of fiber are off-wound from a supply reel to a transfer spool. Half of the transfer spool (110m) is off-wound to another transfer spool. The transfer spools are then positioned on the PCWS, one in the counterclockwise (ccw) supply position and the other in the ride position. Refer to Figure 4-8.
- The fiber is continuously dressed from the tensioner, between the encoder assembly, through the fiber guide, on the surface of the LN-200 coil in the wind position, and finally to the supply spool in the ride position.
- The clockwise (cw) supply spool is placed on the ride position of the LN-200 spool plate. The PCWS is turned on from the PC work station and fiber is unwound from the ccw supply position and wound on the LN-200 spool in the quadrupole mode.



**Figure 4-8. Prototype Coil Winder Station Schematic**

- After one layer is wound, the computer stops the PCWS. The cw supply is removed from the LN-200 spool plate and placed at the cw supply position. The ccw supply spool is then placed on the spool plate and the wind is repeated. After the initial layer, for each supply spool, two layers are wound between spool swaps until the final layer of the last quadrupole. See Figures 4-9 and 4-10 for photographs of the PCWS. Refer to the schematic for component locations.

**4.4.2 Prototype Coil Winder Operating Instructions.** As indicated earlier, the ACWS is automatic; therefore, much of the automation concepts were developed and tested, to the extent possible, on the Prototype Coil Winder Station (PCWS).

To achieve all of this automation required considerable servo loops and computer software control. The computer control was directed toward a menu approach where the operator selects the mode of operation desired and then enters the necessary parameters, refer to Figure 4-11a. This is the first menu from which numerous others fan out for easy operator input. For instance, selecting "Wind Parameters" or "Motion Control" brings up a second menu, Figures 4-11b, 4-11c, etc. It should be noted that Figures 4-11c and 4-11d request considerable detailed information not only about the spools' physical characteristics but also the dynamic operating information such as speed, tension, fiber spacing, fiber diameter, fiber layers and much more. Like the menus before, Figures 4-11e and 4-11f continue on, asking for more detailed information.

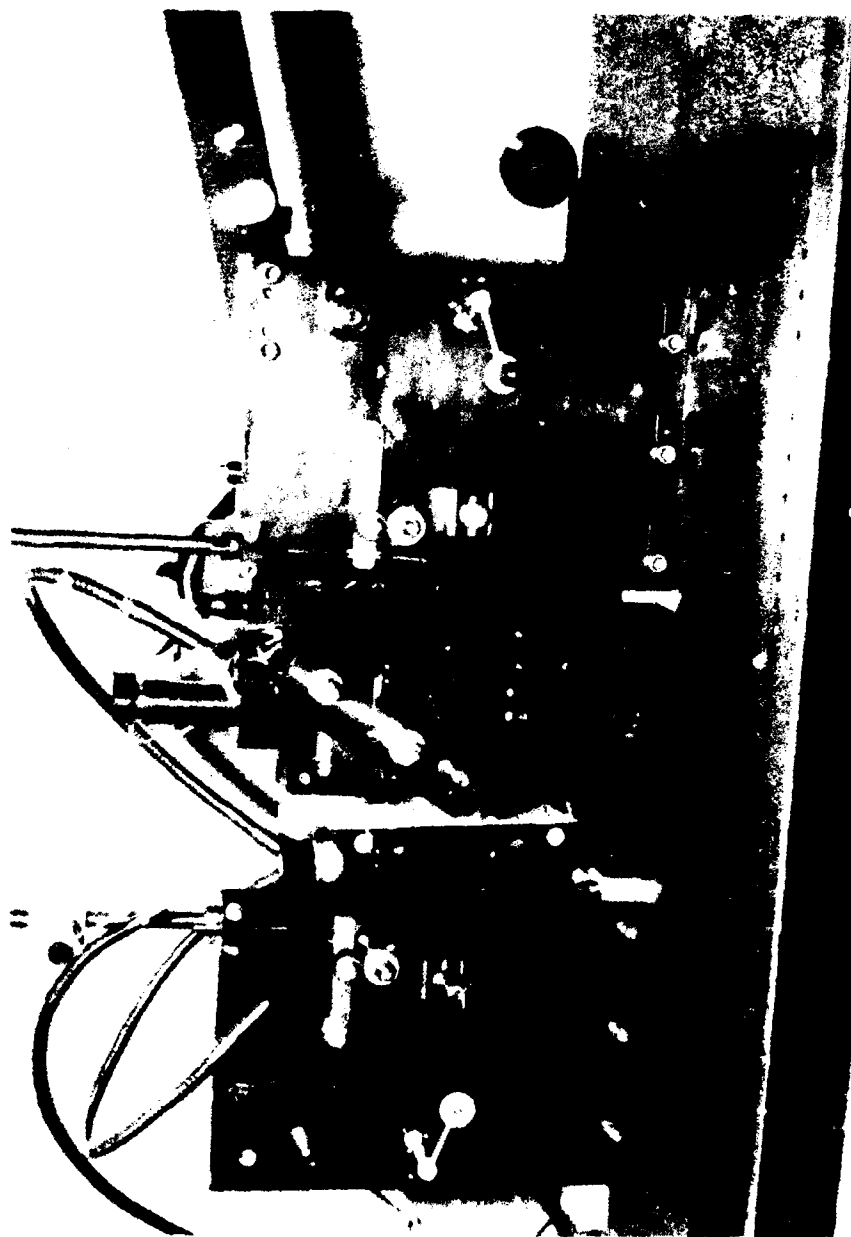


Figure 4-9. Prototype Coil Winder Station



Figure 4-10. Prototype Coil Winder Station Close-up of Spool Mounting Plate

Coil Winder
Coil ID#
Motion Control
Wind Parameters
Bulk Transfer
Wind Coil
Quit

THIS IS THE PRINCIPLE MENU FOR THE  
ENGINEERING WINDER PROTOTYPE  
APPLICATION SOFTWARE

Figure 4-11a. PCWS Principle Menu

Wind Parameters	Motion Control
Coil Statistics Unit Conversion Gap Between Turns Coil Length  Fiber Diameter Outer Diameter of Spool Hub Width of Spool Hub Outer Diameter of Flange Flange to Coil Gap Excess Fiber Transferred Current Layer  Return to Main Menu	Motion Control Statistics Set Wind Feedrate Set Unwind Feedrate  Set Point Digitization Jograte Set Accel/Decel Period Set Wind Tension Set Unwind Tension Initialize Dancers Mount Spool Return to Home Jog Axes Home Axes  Return to Main Menu

## OPERATOR SELECTS APPROPRIATE WIND AND MOTION CONTROL PARAMETERS PRIOR TO INITIATING WIND SEQUENCES

Figure 4-11b. PCWS Wind Parameters and Motion Control Menus

Motion Control	
Coil	
Wind feedrate:	30.00 RPM
Unwind rate:	60.00 RPM
Point Digitize jograte:	10.00 % of max
Accel/Decel period:	4000.00 mS
Wind tension:	1.00 grams
Unwind tension:	30.00 grams
Hit <CR> to proceed...	
Home Axes	
Return to Main Menu	

WITHIN THE MOTION CONTROL SUBMENU, FEEDRATES AND  
OTHER MACHINE CHARACTERISTICS ARE SELECTED

Figure 4-11c. PCWS Coil and Motion Control Submenus

Coil	
Requested length:	1000.00 m
Projected Length:	1023.75 m
Actual Length:	0.00 m
Excess requested:	100.00 m
Fiber diameter:	165.00 $\mu$
Inter-turn gap:	20.00 $\mu$
Flange to coil spacing:	670.00 $\mu$
Spool hub O.D.:	30.48 mm
Spool hub width:	16.51 mm
Spool flange O.D.:	71.55 mm
Projected coil O.D.:	64.32 mm
Number of layers:	84.00
Number of turns/layer:	82.00
Encoder wheel slot:	middle
Hit <CR> to proceed...	

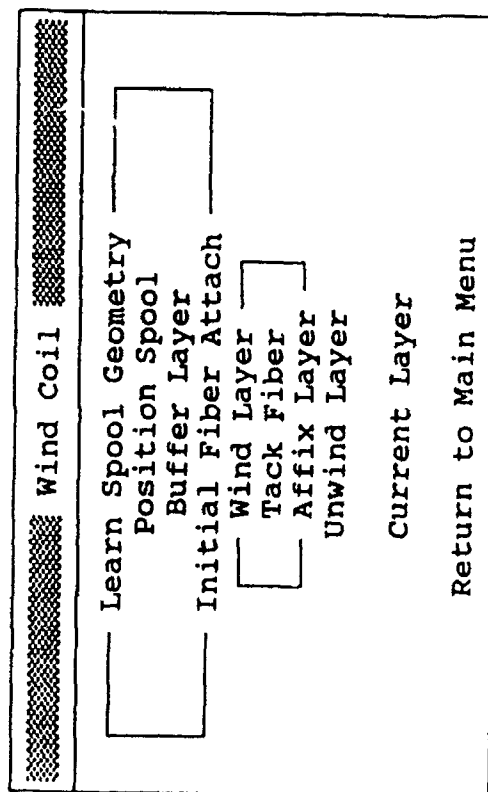
WITHIN THE WIND PARAMETERS SUBMENU,  
SPOOL GEOMETRY IS SPECIFIED

Figure 4-11d. PCWS Wind Parameters Submenu

Bulk Transfers	
<div> <input type="checkbox"/> Learn Spool Geometry  <input type="checkbox"/> Position Spool at Origin  <input type="checkbox"/> Full-length Transfer  <input type="checkbox"/> Half-length Transfer  <input type="checkbox"/> Unwind a Layer  <input type="checkbox"/> Unwind Bulk Spool </div>	
Return to Main Menu	
	Quit

**BULK TRANSFERS ALLOW MOVEMENT OF FIBER FROM  
SHIPPING TO TRANSFER SPOOLS, IN PREPARATION  
FOR SUBSEQUENT WINDING**

**Figure 4-11e. PCWS Bulk Transfer Menu**



DURING WINDING, EACH STAGE OF THE QUADRAPOLE  
WIND PROCESS IS SUCCESSIVELY EXECUTED UNTIL  
THE SPOOL IS COMPLETE

Figure 4-11f. Wind Coil

In summary, for the ACWS to be fully automatic as implied, the menus needed to call for all the conceivable parameters for the computers, sensors, and servos to coordinate properly. As noted earlier, this combination of interacting sensors, servos, and computer software also made the station extremely versatile. It is this versatility that not only provided considerable flexibility in doing more Variability Reduction tasks and SPC  $C_p$  and  $C_{pk}$  experiments, but also in winding future coils with different spool and fiber configurations that are not yet in production. In short, the ACWS is a forward looking machine designed to anticipate future needs as well as meet the needs of current activity.

## **SECTION 5**

### **PHASE II – CRITICAL FACTORS IDENTIFICATION**

#### **INTRODUCTION**

Phase II was organized into the following four activities as part of identifying the Critical Process Factors for the Automatic Coil Winding Station (ACWS):

- Machine Capability Study
- Process Variance Study
- Identify Coil Winding Critical Process Factors
- Identify/Develop Critical Factors Control Methods.

#### **5.1 Machine Capability Study**

The first object of the Machine Capability Study effort was to bring the Prototype Coil Winder Station (PCWS) on-line. The PCWS had limited computer control and manual features for producing coils. In comparison to what was desired, it was grossly deficient for making low-cost coils for production use: The labor factor was deemed far in excess of what would be acceptable for production fiber optic gyros (FOG). Nonetheless, along with the manual coil winding station, the PCWS could be used not only to support the increasing demand for engineering demo gyro build but also for other experimental gyro coil studies. In that sense, it would also support the initial EMPI program with data for doing the Variance Study and Critical Process Factors Identification activities.

To bring the PCWS on-line entailed several modification tasks and tests as described briefly, below.

Identify and correct an intermittent z-axis, vertical movement of the spool which was later traced to a faulty channel.

Increase the dancer pulley wheel radius, the object of which is to ride against the fiber before the guide to maintain a constant, uniform load on the fiber. The diameter is suspect of inducing high stress to the fiber. With a pulley wheel bed (groove) radius less than 0.5 inch, fiber at tangent point can be subjected to tensile stress in excess of the proof test level. Such tensile levels could either damage the fiber jacket or break the fiber itself.

During transfer spool winding, fiber breakage was possible due to variations in conditions of the fiber on the shipping spool, in particular, fiber sticking to itself. This problem was corrected by tuning the shipping spool servo-control and increasing the transfer spool winding tension to 30 grams.

Two 200m test coils were wound with Hitachi fiber to validate the process for an alternative fiber. Both coils had acceptable insertion losses less than 0.5 dB/km.

The wind position spindle was modified to accept a 2-km spool, and then a 1-km practice coil was successfully wound, verifying the capability of the PCWS to wind long coils.

The PCWS was made fully functional and met the design objectives of that time.

In developing data for identification of the critical factors guiding the winding of coils on this station for translation to the design of the ACWS, the machine had to be capable of delivering parts subject to four significant quality factors. These are identified below as performed with LN-200 prototype coils:

- a. **Polarization Holding Parameter** – H-parameter, as this parameter is frequently called, is the ability of a wound coil to preserve the polarized state of the light launched through it. It is expressed as:

$$H = \frac{\text{Power cross - coupled to other polarization}}{\text{Launched Power} \times \text{Length}}$$

Low coil H-parameter is required in order to have low gyro bias temperature sensitivity which manifests itself as gyro drift.

- b. **Insertion Loss** – Low insertion loss of gyro optical components is required in order to obtain reduced gyro angle random walk and to obtain reduced electrical cross-talk – induced bias error since the photodetector signal is larger. Insertion loss is a noise issue in FOG performance.
- c. **Coil Light Transit Time** – Operation of the gyro at the proper frequency (half the inverse of the coil light time) is required in order to eliminate many sources of bias error. For a three-axis gyro, the proper frequencies of each gyro, i.e., transit times of coils, must match one another within 1 percent. Like Polarization Holding or H-parameter, this factor manifests itself as gyro drift.
- d. **Winding Pattern** – All the emphasis of coil winding activities on this program are focused around the quadrupole technique. A detailed description of quadrupole winding pattern is addressed in the Section 3. Like the polarization holding or H-parameter and coil transit time, winding pattern also manifests itself as drift in gyro performance and, therefore, must be carefully studied. See Appendix A for further discussion on optic requirements.

For the quality factors test data, three LN-200 coils were wound on the PCWS in the identical manner and eight coils were wound (previously) on the manual coil winder. Averages of the coils quality factors test data are presented in Table 5-1.

**TABLE 5-1. BENCHMARK PROTOTYPE WINDER VS MANUAL WINDER**

Parameter	Specification (Normalized)	Manual Winder*	Prototype Winder
Polarization Holding	<1	0.61	0.77
Insertion Loss	≤1	0.84 ±0.46	0.95 ±0.22
Coil Transit Time	≤1 ±0.01	1.037 ±0.014	1.04 ±0.005
Winding Time	—	24 hrs	6 hrs
*Sample of 8 coils			

The benchmark test data demonstrates that coils wound on the PCWS meet LN-200 specification performance to the same degree as those coils wound on the manual coil winder station.

## 5.2 Process Variance Study

The purpose of the Process Variance Study, using the PCWS as a test bed, was twofold:

- Determine the ability to control geometrical factors during coil winding, and
- Assess the quality of the wound coils in terms of geometrical measurements

To accomplish this task required being able to target coil geometrics (ability to assess and ensure a finite fiber gap), control variance of geometry from coil to coil, and control variances of geometry within each coil.

The following four-element plan was devised to address this matter:

1. Design of experiment (DOE), with particular emphasis on Taguchi process
2. Start with a small orthogonal array in the beginning and expand as necessary
3. Make three repetitious experimental coils
4. Perform a cross-sectional analysis of each coil to determine the results.

Having established the above plan, effort then focused on selecting the means to carry it out. This required careful selection of the appropriate hardware. The PCWS provided the experimental apparatus for the basic winding tests. Program costs were minimized by selection of inexpensive spools and low cost geometrical fiber of the appropriate outside diameter, length, and jacket material. As stated before, gap and layer control is the main focus at this time; therefore, there was no need to use the regular higher-priced gyro optical fiber. Last, of course, the quadrupole wind was utilized.

With the hardware selection established, certain dynamic characteristics had to be emphasized. Some of these were self-imposed constants while the others were variables. The constants were winding tension (approximately 3 grams), winding speed (approximately 30 rpm), and flange (of spool) -to-fiber gap (approximately 300 to 400  $\mu\text{m}$ ). The variables at this time, were fiber guide position and gap between fiber turns, commonly referred to as pitch.

**5.2.1 Quality Characteristics.** Quality characteristics for the Process Variance Study were:

- Gap between turns
- Gap or thickness between layers
- Fiber-to-flange gap, i.e., its value as a function of coil radius

These elements are essential for good winding control.

To ascertain these quality features required experimental measurements that consisted of the following:

- Section, polish, and photograph the wound spool
- Microscopically measure gap at various locations throughout the spool.

The final data reduction of the Process Variance Study utilized the Taguchi analysis and other statistical methods.

**5.2.2 Taguchi Orthogonal Array.** Initial studies of coil winding control and process factors were started as soon as the PCWS was brought on-line. The Taguchi orthogonal array was used. The earliest was the Taguchi L4 array (see Figure 5-1), where the fiber gap was varied as a function of the guide position. It was noted immediately that as rough runs were attempted in preparation to do the Taguchi experimental runs, excessive crossovers developed, making it imperative to abort the wind. At this point, crossovers surfaced as an extremely critical process factor.

### **5.3 Identify Critical Process Factors and Control Methods**

From the initial Process Variance Study results it was apparent that a much broader plan had to be developed that would address process factors critical to crossovers. This gave rise to the expanded L8 array (see Figures 5-2, 5-3 and then L9 (Figure 5-4)), which embodied more variables. These variables focused on the critical factors influencing crossover such as fiber gap, fiber guide position, winding speed, and fiber tension. Further, these tests were limited to a single layer so that the idealized, smooth, arbor surface condition would not be an influencing factor at this time, i.e., the first layer is laid directly on the aluminum arbor. When these critical factors were better understood and able to be controlled, the tests could then gravitate to the less idealized surface, such as a subsequent layer being laid down on another layer. See Figure 5-4 for the final results.

EXPERIMENTAL CONDITIONS			RESULTS		
	FIBER GAP	GUIDE POSITION	TRIAL 1	TRIAL 2	TRIAL 3
1	SMALL	INSIDE			
2	LARGE	OUTSIDE			
3	SMALL	OUTSIDE			
4	LARGE	INSIDE			

**Figure 5-1. Taguchi L4 Orthogonal Array**

	CONTROL FACTORS	LEVEL 1	LEVEL 2	UNITS
1	APPLIED TENSION (ACTUAL TENSION)	4	10	GRAMS
2	PITCH (GAP BETWEEN TURN)	170	195	MICRONS
3	SPOOL TO GUIDE DISTANCE	LO	HI	GRAMS
4	WIND SPEED	LO	HI	R.P.M.
NOISE FACTORS				

**Figure 5-2. Critical Process Factor Experiment**

MATRIX L8					NOISE		
CONTROL FACTORS					T1	T2	T3
	1	2	3	4	-55	30	95
1	4	170	LO	LO			
2	4	195	HI	HI			
3	10	170	LO	HI			
4	10	195	HI	LO			
5	4	170	HI	LO			
6	4	195	LO	HI			
7	10	170	HI	HI			
8	10	195	LO	LO			

**Figure 5-3. Critical Process Factors Experiment Taguchi Array**

CROSSEVERS

1.9 (3*4) Array				
#	A	B	C	D
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

Main Factors				
Fiber Gap	Gde.Pos.	Speed	Tension	
20	Inside	50	lowest	
20	Outside	100	10	
20	Way Out	150	20	
40	Inside	100	20	
40	Outside	150	lowest	
40	Way Out	50	10	
60	Inside	150	10	
60	Outside	50	20	
60	Way Out	100	lowest	

Spool A-1		Spool B-1	
Run#1	Run#2	Run#1	Run#2
41	39	0	2
29	34	9	0
9	4	0	0
2	0	0	0
0	4	0	0
0	0	0	0
0	0	7	3
0	0	0	0
0	0	0	0

Avg.	STD	Total
20.5	22.55	82
18	16.15	72
3.25	4.272	13
0.5	1	2
1	2	4
0	0	0
2.5	3.317	10
0	0	0
0	0	0

Avg. = 9	Avg. = 1.167	Avg. = 5.083	183
STD = 15.06	STD = 2.64	STD = 11.38	

Response Table w r t # of Crossovers				Strong Effect		Paper Champ	
Level	Fiber Gap	Gde. Pos.	Speed	Tension	Fiber Gap	A	2
1	13.9	7.8	6.8	7.2		B	3
2	0.5	6.3	6.2	6.8		C	3
3	0.8	1.1	2.3	1.3		D	3
Difference	13.4	6.7	4.5	5.9			

Figure 5-4. EMPI Coil Wind Experiment — One-Layer Wind on Aluminum Mandrel

The Taguchi layer wind experiments provided many observations.

- A large nominal fiber gap allows variations in actual gap with fewer crossovers
- Number of crossovers is dependent on quality of the underlying surface
- Fiber can be a significant noise source
- Some improvement could be obtained by grounding the guides and installing an air ionizer
- Noise factors exist that continue to cause large variations in fiber gap, and thus crossovers.

The above observations prompted considerable analysis concerning possible causes for crossovers. Appendix B gives a refresher explanation of crossovers with the below identified items suggesting cause.

- |                                                   |                                                                                       |
|---------------------------------------------------|---------------------------------------------------------------------------------------|
| • Variations in fiber diameter and fiber "memory" | – Treated as noise                                                                    |
| • Nonuniformity of previous layer                 | – Treated as noise                                                                    |
| • Static charge                                   | – Experiments show improvement with grounding and air ionizer                         |
| • Fiber twist                                     | – Preliminary experiments showed no effect                                            |
| • Tension variation (spikes)                      | – Experiments show small tension spikes have no effect                                |
| • Fiber defects (e.g., bulges and neckdowns)      | – No correlation found to date                                                        |
| • Motion control errors                           | – Preliminary analysis indicated negligible effect due to variation in guide movement |
| • Particles on fiber or spool                     | – Fiber storage improved, air ionizer installed – additional action may be required   |
| • Fiber guide                                     | – New guide in designed experiments performed                                         |

Through careful analysis of the possible cause and effect above and many experimental tests, it became conclusive that the fiber guide itself is the most critical control factor. Thus, it was time to move on to the situation of winding layers of fiber on the rough surface of a previous layer and not the idealized smooth arbor. For the Taguchi L9 array addressing all these variables and the experimental results, see Figures 5-5 and 5-6 and Table 5-2. By this time however, preliminary experience from the operator was suggesting that the guide is the largest contributor to crossovers. What specific element it is about the guide remained to be determined. More will be discussed on this in Phase III under Variability Reduction.

Meanwhile, frequent questions were asked: do crossovers actually, indeed, affect optical performance of the coil, i.e., loss, H-parameter? What level of crossovers are tolerable? The L9 array using 4-layer coils was planned for measuring loss and H-parameter at room temperature, and an L4 array using 200 meters of fiber for measuring loss, H-parameter, and also transit time. See Figures 5-7 and 5-8 for the arrays.

Analysis of the gyro performance with crossovers revealed that the issues of manufacturability were more important. The focus of the effort then shifted to revising the guide design such that the winding process could be completed with minimum crossovers.

**TABLE 5-2. SUMMARY OF SINGLE LAYER (90 TURNS) L9 TAGUCHI EXPERIMENTS**

Experiment	Average Number of Crossovers/layer	Strong Effect	Recommended Value
Fiber on Aluminum	5	Fiber Gap	40 $\mu\text{m}$
Fiber on Fiber	15	Fiber Gap	60 $\mu\text{m}$
Fiber on Aluminum with ground and Air Ionizer	2	Fiber Gap	40 or 60 $\mu\text{m}$
Confirmation coil wound using: GAP = 60 $\mu\text{m}$ , Guide Position = Way Out, Speed = 100 rpm, Tension = Lower (3 grams)			
First 12 layers of coil were wound successfully without crossovers – layers 13-20 had crossovers			

# CROSSEOVERS

L9 (3 <sup>4</sup> ) Array					Main Factors					Spool A-1		Spool B-1		Avg.	STD	Total	
#	A	B	C	D	Fiber Gap	Gde. Pos.	Speed	Tension	Run#1	Run#2	Run#1	Run#2					
1	1	1	1	1	20	Inside	50	lowest	33	39	37	33	35.5	3	142		
2	1	2	2	2	20	Outside	100	10	22	22	7	10	15.25	7.89	61		
3	1	3	3	3	20	Way Out	150	20	18	23	15	18	10.5	3.317	74		
4	2	1	2	3	40	Inside	100	20	16	16	18	17	16.75	0.957	67		
5	2	2	3	1	40	Outside	150	lowest	23	19	23	22	21.75	1.893	87		
6	2	3	1	2	40	Way Out	50	10	21	17	22	20	20	2.16	80		
7	3	1	3	2	60	Inside	150	10	3	5	6	4	4.5	1.291	18		
8	3	2	1	3	60	Outside	50	20	0	0	1	0	0.25	0.5	1		
9	3	3	2	1	60	Way Out	100	lowest	0	0	0	3	0.75	1.5	3		
Response Table w.r.t. # of Crossovers										Avg. = 15.39		Avg. = 14.22		Avg. = 14.81		533	
										STD = 11.72		STD = 11.08		STD = 11.26			

Response Table w.r.t. # of Crossovers				Strong Effect		Paper Champ	
Level	Fiber Gap	Gde.Pos.	Speed	Tension	Fiber Gap	A	3
1	23.1	18.9	18.6	19.3		B	2
2	19.5	12.4	10.9	13.3		C	2
3	1.8	13.1	14.9	11.8		D	3
Difference	21.3	6.5	7.7	7.5			

Figure 5-5. EMPI Coil Wind Experiment — One-Layer Wind on Fiber Layer

L9(3 <sup>4</sup> ) Array					Main Factors				Spool A-1		CROSSOVERS			
#	A	B	C	D	Fiber Gap	Gde. Pos.	Speed	Tension	Run#1	Run#2	Avg.	STD	Total	
1	1	1	1	1	20	Inside	50	lowest	14	8	11	4.243	22	
2	1	2	2	2	20	Outside	100	10	0	2	1	1.414	2	
3	1	3	3	3	20	Way Out	150	20	2	1	1.5	0.707	3	
4	2	1	2	3	40	Inside	100	20	0	0	0	0	0	
5	2	2	3	1	40	Outside	150	lowest	0	0	0	0	0	
6	2	3	1	2	40	Way Out	50	10	0	0	0	0	0	
7	3	1	3	2	60	Inside	150	10	0	0	0	0	0	
8	3	2	1	3	60	Outside	50	20	0	0	0	0	0	
9	3	3	2	1	60	Way Out	100	lowest	0	0	0	0	0	
									Avg. = 1.5		Avg. = 1.5		27	
									STD = 3.666		STD = 3.666			
Averages					Response Table w.r.t. # of Crossovers				Strong Effect		Paper Champ			
Level	Fiber Gap	Gde. Pos.	Speed	Tension	Fiber Gap	Gde. Pos.	Speed	Tension	Fiber Gap		A	B	C	D
1	4.5	3.7	3.7	3.7							3	2	2	2
2	0	0.3	0.3	0.3										
3	0	0.5	0.5	0.5										
Difference	4.5	3.4	3.4	3.4										

Figure 5-6. Fiber Guides Grounded and Air Ionizer Installed

L9 (3 <sup>4</sup> ) ARRAY				MAIN FACTORS				LOSS	h-PARAMETER	# CROSSOVERS @ LAYER			
#	A	B	C	D	FIBER GAP	GDE. POS.	SPEED			1	2	3	4
1	1	1	1	1	20	INSIDE	50	TENSION					
								LOWEST					
2	1	2	2	2	20	OUTSIDE	100	10					
3	1	3	3	3	20	WAY OUT	150	20					
4	2	1	2	3	40	INSIDE	100	20					
5	2	2	3	1	40	OUTSIDE	150	LOWEST					
6	2	3	1	2	40	WAY OUT	50	10					
7	3	1	3	2	60	INSIDE	150	10					
8	3	2	1	3	60	OUTSIDE	50	20					
9	3	3	2	1	60	WAY OUT	100	LOWEST					

Figure 5-7. L9 Taguchi Array for Four-Layer Wind Experiment

L4 ARRAY			MAIN FACTORS*					
#	A	B	C			LOSS	h-PARAMETER	TRANSIT TIME
1	1	1	1					
2	1	2	2					
3	2	1	2					
4	2	2	1					

\* MAIN FACTORS TO BE DETERMINED FROM  
RESULTS OF L9 FOUR-LAYER EXPERIMENT

Figure 5-8. L4 Taguchi Array for 200-meter Coll Wind Experiment

## SECTION 6

### PHASE III – VARIABILITY REDUCTION PROGRAM

#### INTRODUCTION

Phase III Variability Reduction Program was organized into the following activity areas:

- QFD Matrix
- Additional PCWS Experiments
  - Variance Study (Geometric)
  - Critical Factors Identification (Optics)
  - ACWS Experiments.

#### 6.1 QFD Matrix

In Phase I, general development of the QFD Matrix was discussed. Questions answered were: what are the goals of the matrix for the ACWS; what are the ACWS coil design requirements and, what are the ACWS manufacturing requirements? Then Phase II, Critical Factors Identification, brought out the critical parameters that determine the success of the coil winding such as H-parameter, insertion loss, coil light transit time, and winding pattern and how these can affect drift, etc. Phase III required a variability reduction effort on the PCWS and a continuing detailed study of the QFD Matrix.

**6.1.1 Discussion of the QFD Matrix.** The QFD Matrix, Figure 6-1, proved a valuable tool in addressing and tracking all the various requirements, goals, and tradeoffs encountered in the ACWS design.

To the far left side of the matrix, under the **WHATs** heading, are three columns. Working from the first column at the far left, are broad, general functions which get more specific when stepping over into the next two adjacent columns to its right. Generally speaking, the **WHATs** column identifies what the customer wants the ACWS to do. All these requirements are played against how the requirements are to be met; thus, the general title **HOWs**.

The **HOWs** heading generally reflects the specific generic hardware or software, etc., needed in the station to satisfy the function requirements identified under the **WHATs** heading.

**Figure 6–1. Automatic Coil Wind Station (ACWS) QFD Design Matrix**

The fourth column, **IMPORTANCE**, is a number collectively weighed by a committee consisting of engineering, manufacturing, quality assurance, and other essential disciplines. These numbers are essential as tradeoffs become necessary. They correlate with the numbers one through five under the second column from the far right. Some comments are in order about this latter column.

It should be noted that weighing factors were determined for both the PCWS and the planned ACWS. These are shown in the matrix as one series connected by a square dot pattern which reflect the hindsight judgement of the PCWS while the other, those connected by the circular dot pattern, reflect the foresight judgement for the ACWS. Collectively, they provide credible weighing analysis for the ACWS.

In assessing the weighing factors for these two stations, it is apparent that the PCWS, under the heading **PROTO**, contained many "1" factors, indicating it had poor production value. This implies that it was not cost effective in achieving the objective required by the customer as a production machine. On the other hand, the ACWS, under the heading **PROD** for production, showed many heavily weighed "5" factors indicating that many of the desired goals will be satisfied.

On balance, the QFD Matrix proved a very dynamic and useful tool. This was especially true for the ACWS, though tradeoff studies were numerous, the effort resulted in a station that met all the basic goals of the customer.

## **6.2 Additional PCWS Experiments**

While the PCWS and QFD played a major role in the design of the ACWS, tests on the PCWS under Phase II, clearly identified the fiber guide as a critical factor which could well determine the success of the ACWS. Therefore, as a result of Phase II, much of the Variability Reduction effort, Phase III, focused on fiber guide and the attachment influencing its design and function.

As noted earlier, the PCWS was brought on-line to be used to experiment and develop items and techniques for the ACWS. Consistent with that was a Variance Study (Geometric), Critical Factors Identification (optics), and ACWS experiments.

**6.2.1 Variance Study.** To optimize the fiber payguide assembly, it was necessary to step back and review its function.

- It performs the payout of fiber from the transfer spools onto the sensor spool mounted on the spindle axis
- It must operate under programmable, served fiber tension

- It comes into play with fiber length measurement using an encoder-based capstan/pinch roller pair
- It coerces the fiber to the point of contact with the sensor spool being wound.

The payguide assembly went through several iterations resulting from the variability reduction effort. As noted, crossovers were identified as the critical problem with fiber gap the underlying cause. Therefore, to control fiber crossover, it is necessary to control fiber gap. But to control fiber gap requires a fiber payout guide assembly that can perform such a task consistently and reliably. Meanwhile, earlier tests on the PCWS already showed that the baseline fiber guide mechanism could not control the gap. Consequently, crossovers were uncontrollable. For details on the payguide assembly (PGA) development, see Appendix C; otherwise, a summary of the fiber guide versions and respective results are as follows:

Version	Problem/Results
Baseline or original design	<ul style="list-style-type: none"> <li>- Fiber frequently jumped out of guide</li> <li>- Guiding was poor</li> <li>- Extensive Crossovers</li> <li>- Greater flange to coil gap</li> <li>- Guide could not be taken tangent to spool</li> <li>- Fiber abrasion</li> </ul>
Revision 1	<ul style="list-style-type: none"> <li>- Still lost fiber from guide</li> <li>- Improved geometric quality over baseline design</li> <li>- Fiber abrasion</li> </ul>
Revision 2	<ul style="list-style-type: none"> <li>- Very minimal crossovers</li> <li>- Fiber did not jump out of guide</li> <li>- Fiber abrasion</li> </ul>
Revision 3	<ul style="list-style-type: none"> <li>- Eliminated abrasion</li> <li>- Good crossover control</li> </ul>

The payguide was such a critical factor in handling the fiber that involved a collaborative effort with the fiber manufacturer and the PCWS and ACWS engineers. The former identified the critical elements in handling the fiber, including its storage, while the latter identified the application and objective. Tradeoffs were not viewed favorably as they could instill not only damage to the fiber jacket but to the optical fiber as well. For instance, the vendor even identified simple benign storage as a critical issue; i.e., if not positioned properly, physically, stress could develop. The culmination of all these sensitive fiber issues compounded the already difficult task on how to lay down fiber while avoiding fiber crossover.

**6.2.2 Critical Factors Identification.** Critical factors in the Variability Reduction effort focused on solving crossover problems resulting from the payguide's inability to control fiber gap, a leading cause of crossover, and also on some side effects caused by the guide: Abrasion.

As noted above, abrasion was a critical factor. Abrasion to the fiber jacket can ultimately create micro fractures in the fiber which affect the optic characteristic of the fiber. Additionally, it can cause high stress points in the fiber where the jacket may be completely abraded off. Abrasion is critical to the optical performance of the coil and subsequently the FOG.

Until Revision 3 iteration, fiber guide emphasis focused on fiber crossover with the thought that abrasion could be simply eliminated by a good honing or polishing of the fiber guide surface. The material selected because it could handle physical abuse would not take a good electropolish. This was further compounded by the small size of the groove. Both Revision 1 and Revision 2 configurations attempted to design around this problem but none were successful. This ultimately led to Revision 3; a wheel, where there would be no dragging surfaces against the fiber. The wheel concept was initially tested on the PCWS with final development being done on the ACWS. The success of the wheel was a major step forward and not without its own unique problems as noted by additional details in Appendix C.

**6.2.3 ACWS Experiments.** With successful development of the fiber guide and payout assembly, it was then possible to exercise all the features of the ACWS. A brief review of some of these features follows:

- Guide fiber to point of tangency on spool
- Modular, modifiable
- No slip rings
- Only six motion control axes plus tension control
- Supports present and anticipated coil fabrication processes
- Minimal touch labor
- Fully programmable from menus.

To test the ACWS, several spools were wound and tested as indicated below.

- 60 minutes/coil (machine time), was 24 hours/coil on the manual station
- 15 minutes/coil (touch or hands-on-time), was 24 hours/coil on manual station
- Yield was not projected at this time due to the small sample.

These are significant improvements and generally meet the goals of the station. Further improvements are expected as the operator gains more experience on the station.

It was not possible to perform preliminary SPC  $C_p$  and  $C_{pk}$  studies on the ACWS because the customer (factory) was pressing for station delivery. Therefore, that data collection was deferred to the production site and will be addressed in Phase IV, SPC Implementation.

## **SECTION 7**

### **PHASE IV – SPC IMPLEMENTATION**

#### **LITTON TQM OVERVIEW**

As stated earlier, TQM has been implemented at Litton since early 1980. At that time teaming classes were initiated in production facility to cut costs, increase reliability, reduced scrappage, etc. This effort met with such success that it was eventually expanded to include all of engineering as well. Eventually, as part of TQM, SPC became a way of life, producing a tremendous data base for numerous types of studies, analysis and forecasts.

With the advent of the EMPI program, Litton was well positioned to bring it on-line with an even broader aspect of TQM. Thus, Litton's TQM effort under EMPI consisted of QFD, Concurrent Engineering, Taguchi Methods, SPC, and CIM. The SPC implementation part of the EMPI effort on the ACWS was a test of whether all the concerted TQM effort produced a cost effective coil winding station or not. A brief review of Litton's earlier TQM efforts are presented here to show how these facilitated the EMPI SPC effort.

For the most cost-effective SPC results, teamwork is essential from initial stages of the design right up through production, i.e., the mind-set must be conditioned early-on toward the TQM objective. With Litton's TQM having been in effect 10 years before the advent of EMPI, the mind set was well conditioned for full implementation on EMPI's ACWS effort. Despite Litton's earlier success with TQM, they continued to explore new additions to their TQM program, and these were folded into the EMPI program as deemed feasible. Some of the conditioning undertaken in the past and in full force today is as follows:

- Empowering the employee
- Removing organizational barriers
- Enhancing communications
- Driving out fear
- Enhancing recognition
- Changing the structure (span of support)
- Streamlining process (eliminate nonvalue-added effort)
- Providing the TQM tools (stated above).

To further enhance the above conditioning, Litton vested management with a broad authority as listed below:

- Extensive employee involvement process
- Active customer teaming
- Aggressive supplier partnership program
- Elaborate variability reduction system employed throughout the Division
- Concurrent engineering approach applied to all new designs.

As evidence of Litton's early success with TQM, Figure 7-1 shows that as the training gradually expanded to include all employees at the Salt Lake City (SLC) production facility, there was a corresponding drop in the percent of scrappage. This scrappage did not include any fiber optic gyro (FOG) effort at the time, because that was still in the developmental stage and only production activity is performed at SLC. Nonetheless, the mind-set was already established there long enough to be a valuable asset toward implementing the use of TQM on the EMPI ACWS program.

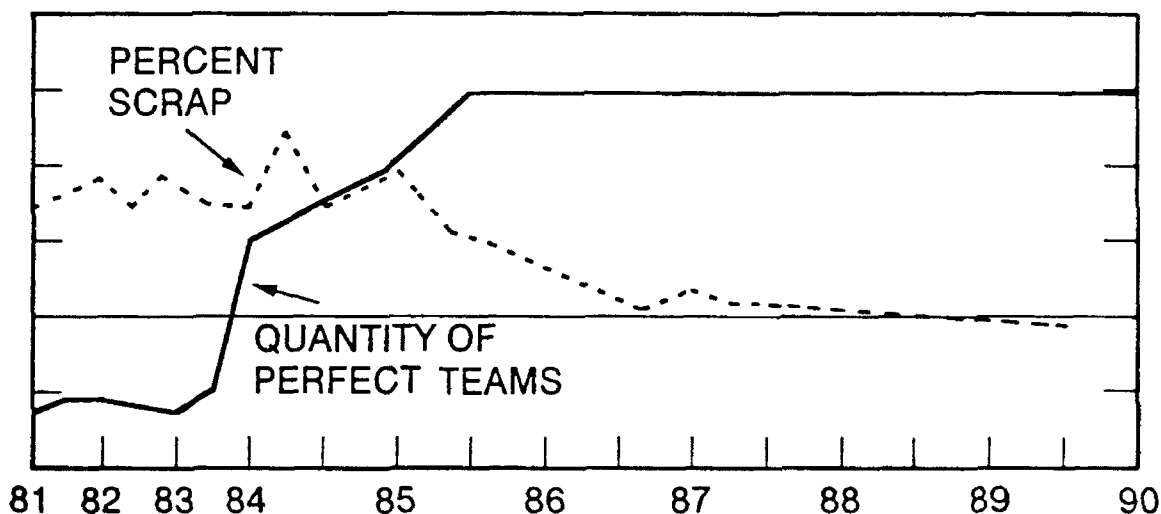


Figure 7-1. Percent Scrap – Salt Lake Facility Plant Total

TQM and SPC policies and procedures were modified only to the extent of any special requirements unique to the manufacturing (winding) and testing of fiber optic coils. General implementation of FOG coil winding SPC consisted of the following:

- Database maintained on a Sun Sparc Station network using Unix-based Ingres package
- All wind parameters and test results maintained in data base
- Test data transferred automatically to database
- Operators shown SPC charts during parameter input

- Operators and engineers warned when an "out of control" condition is encountered in the database, based on an editable list of "rules"
- SPC reports routinely produced using commercial statistical package.

It should be noted that the SPC database is electronic. This offers numerous advantages such as described below:

- Data is automatically collected and transferred to database, reducing labor required for data collection
- Data may be easily displayed and analyzed in various formats
- Data reduction and correlation studies are simplified and can be automated
- Correlation to data from tests done at higher assembly levels are simplified and can be automated
- Because data collection and reduction time is reduced, more experiments can be performed.

Some of the process control charts available under Litton's programs are itemized here:

- For Variables
  - Item Chart – (also referred to as I- or X-charts) plots individual items chronologically
  - Median Chart – similar to ITEM chart but gives more weight to occasional wild shot values
  - Moving Average Chart – both uniformly and exponentially weighed
  - R-Chart – plots range of subgroups
  - Sigma Chart – plots standard deviation of subgroups
  - X-Chart – plots average of subgroups
- For Attributes
  - c-Chart – plots number of (#) defects per unit with constant number of units per subgroup
  - np-Chart – plots number or rejected items in constant sized subgroups
  - p-Chart – plots fraction or percentage of subgroup rejected
  - u-Chart – plots defects per unit with variable number of units per subgroup

- Miscellaneous Charts and Design of Experiments
  - Cumulative Sum Chart – running summation of process deviation from a preselected reference or target value
  - Pareto Diagram – also referred to as ABC diagram, useful for showing what portion of a total problem smaller problems comprise
  - Process Capability Chart – provides capability information including  $C_{pk}$
  - Design of Experiment – tools including Taguchi,  $2^k$  factorial, box-Behnken and central composite for linear and nonlinear modeling.

### 7.1 SPC Implementation on the ACWS

Consistent with Litton's overall SPC program, the following partial list makes up the specific SPC database as it relates to coils wound on the ACWS:

- |                                 |                                  |
|---------------------------------|----------------------------------|
| • Desired length                | • Fiber diameter                 |
| • Physical length               | • Wind feed rate                 |
| • Optical length                | • Actual coil OD                 |
| • Turns/layer                   | • Operator                       |
| • Interturn gap                 | • Coil wind begin time and date  |
| • Wind tension                  | • Coil wind finish time and date |
| • Spool hub width               | • Operator comments              |
| • Spool hub outer diameter (OD) | • Fiber lot number               |
| • Guide hover height            | • Station calibration dates      |
| • Flare-coil gap                |                                  |

With 10 years of successful experience already behind Litton implementing TQM and subsequently SPC on other programs, it is anticipated that SPC will manifestly reap early benefits on the ACWS through the following improvements savings:

- Significant cost savings and product quality improvements projected in comparison to the manual station
- Significant improvements in coil performance achieved through process changes using classical and Taguchi experiments
- Experimentation and process improvement to continue with the ACWS
- SPC will play an important role in reducing variability and continued improvement of the manufacturing process.

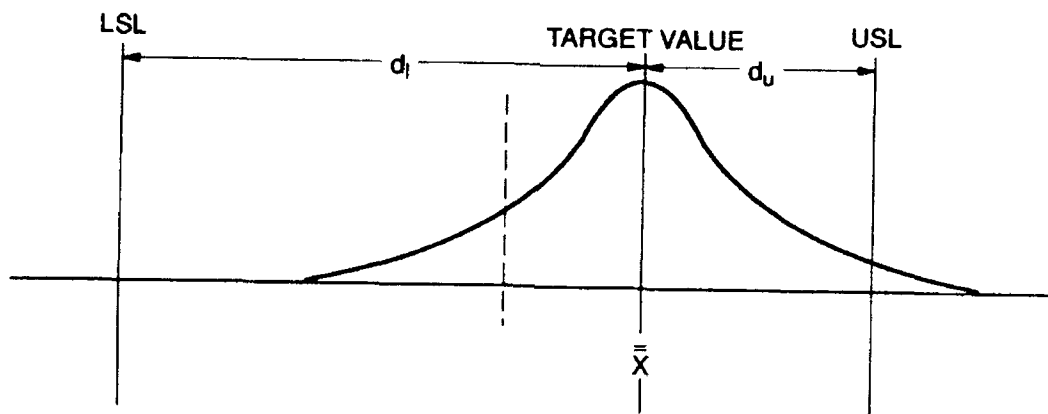
Currently, the ACWS is on-line and produced its first 25 spools under the SPC format identified above. For these spools, as stated above, emphasis focused on several parameters:

- Auto wind, length
- Maximum cross coupling
- Cross coupling at 25°C
- Loss at 25°C
- Maximum loss (-55°C to 105°C).

Process capability indices  $C_p$  and  $C_{pk}$  were calculated for each parameter. Figure 7-2 is offered as a reminder to the reader of their respective meanings.

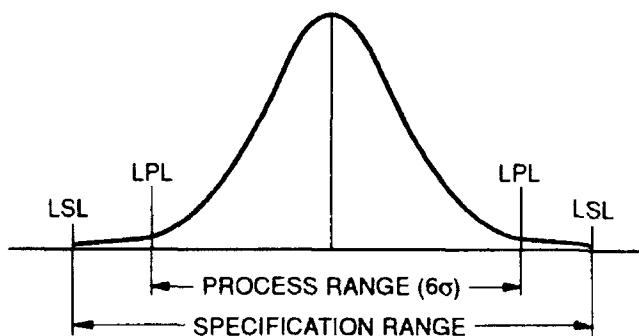
## **7.2 SPC Results on the ACWS**

Item charts and process capability charts were generated for the first production run of 25 parts. Though it is a relatively small sample, useful results were obtained. For instance, examination of the four sets of parametric curves, auto wind length, cross coupling at 25°C, loss at 25°C, and maximum loss (across temperature) (Figures 7-3, 7-4, 7-5, and 7-6, respectively), shows that although all results indicate acceptable parts, additional savings may be realized through some relaxation of the FOG coil specification. On the other hand, the remaining set of curves, maximum cross coupling, Figure 7-7), indicate an out-of-specification condition and associated scrappage. Therefore, these five sets of parameters are being reviewed collectively to see if relaxation of the acceptable ones may be achieved without leading to additional scrappage on the one. The process of revising the specification, optimizing the process, and monitoring key process variables will continue throughout production of FOG coils at Litton.



$$C_{Pk} = \min \left[ \frac{USL - \bar{X}}{(3\sigma)}, \frac{\bar{X} - LSL}{(3\sigma)} \right] = \frac{\text{PROCESS MEAN} - \text{NEARER SPEC LIMIT}}{(3\sigma)} = \frac{d_u}{(3\sigma)}$$

(FOR ABOVE FIGURE) WHERE  $\bar{X}$  = PROCESS MEAN



PROCESS CAPABILITY IS THE RATIO OF SPECIFICATION RANGE TO PROCESS RANGE

$$C_p = \frac{\text{SPEC RANGE}}{\text{PROCESS RANGE}} = \frac{(USL - LSL)}{(6\sigma)}$$

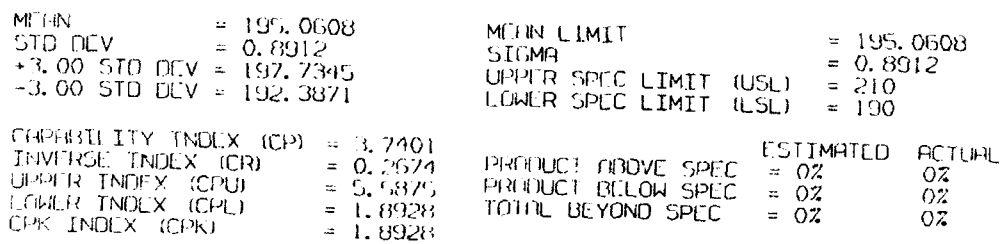
WHERE  $\sigma$  = STANDARD DEVIATION OF THE MEASURED CHARACTERISTIC

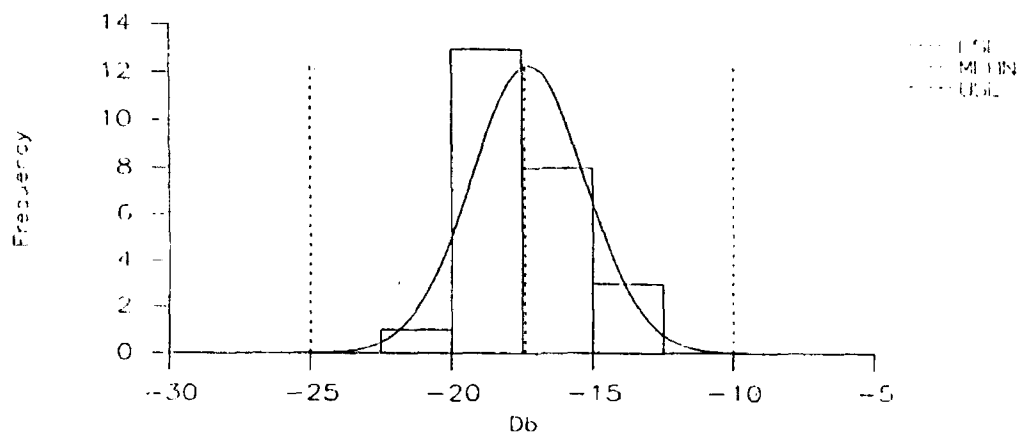
PROCESS CAPABILITY ( $C_p$ )	PPM DEFECTIVE
0.60	71,800
0.90	6,900
1.00	2,700
1.33	63
1.67	<1
4.50	<<1 (PPB)

LPL = LOWER PROCESS LIMIT  
UPL = UPPER PROCESS LIMIT

LSL = LOWER SPECIFICATION LIMIT  
USL = UPPER SPECIFICATION LIMIT

Figure 7-2. Process Capability Relationships and Index



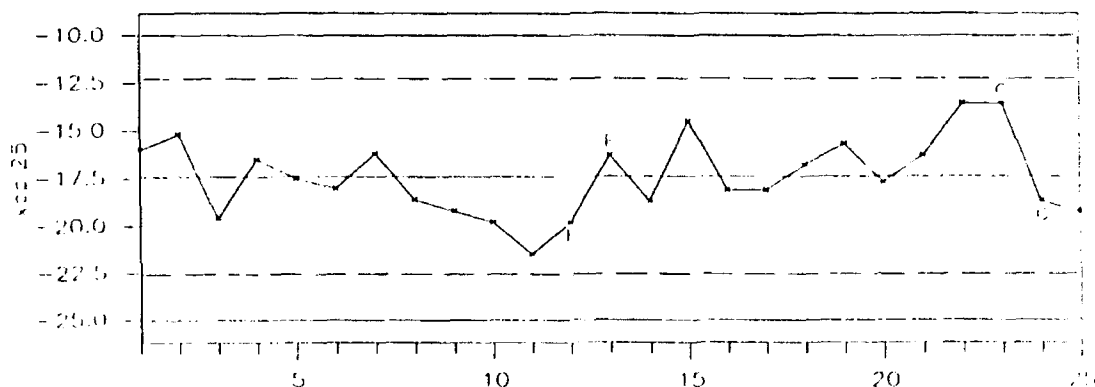


MEAN = -17.412  
STD DEV = 2.0237  
+3.00 STD DEV = -11.391  
-3.00 STD DEV = -23.483

MEAN LIMIT = -17.412  
STANDARD = 2.0237  
UPPER SPEC LIMIT (USL) = -10  
LOWER SPEC LIMIT (LSL) = -25

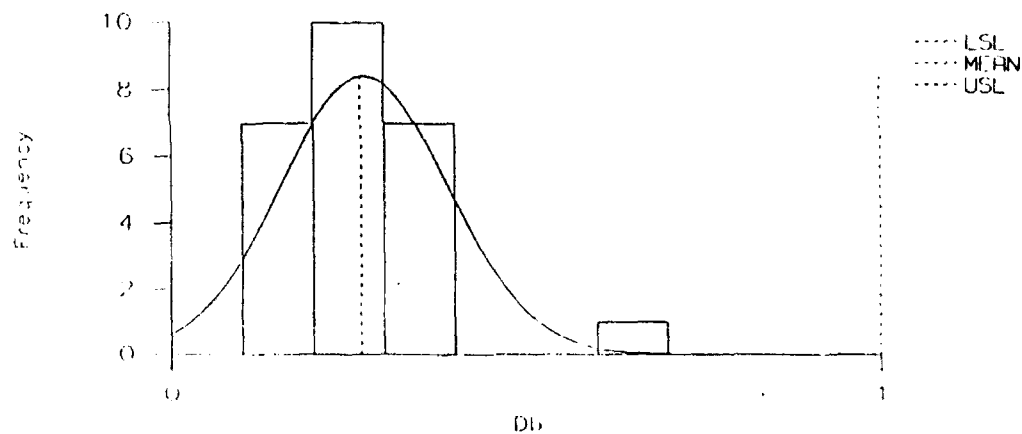
CAPABILITY INDEX (CPI) = 1.2359  
INVERSE INDEX (CIR) = 0.8095  
UPPER INDEX (CPIU) = 1.2209  
LOWER INDEX (CPL) = 1.2499  
CPK INDEX (CPK) = 1.2209

	ESTIMATED	ACTUAL
PRODUCT ABOVE SPEC	= 0.01%	0%
PRODUCT BELOW SPEC	= 0.01%	0%
TOTAL BEYOND SPEC	= 0.02%	0%



--- LCL = -22.565	--- CL = -17.412	--- UCL = -12.559
--- LSL = -25.000		--- USL = -10.000
Subgroups : 25	Control : 3.00 sigma	Rules : AT&T
Rules Violated: C) 2 of 3 successive points in upper /zone A or beyond F) 4 of 5 successive points in lower /zone B or beyond		

Figure 7-4. Cross Coupling at 25°C

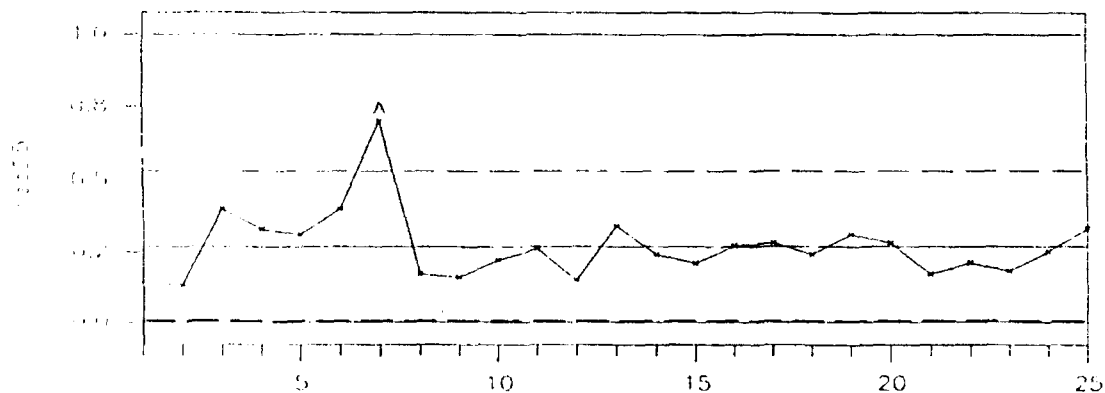


MEAN = 0.2672  
STDEV = 0.1186  
ALGO STDEV = 0.6228  
ALGO STDEV = 0.0885

MEAN LIMIT = 0.2672  
SIGMA = 0.1186  
UPPER SPEC LIMIT (USL) = 1  
LOWER SPEC LIMIT (LSL) = 0

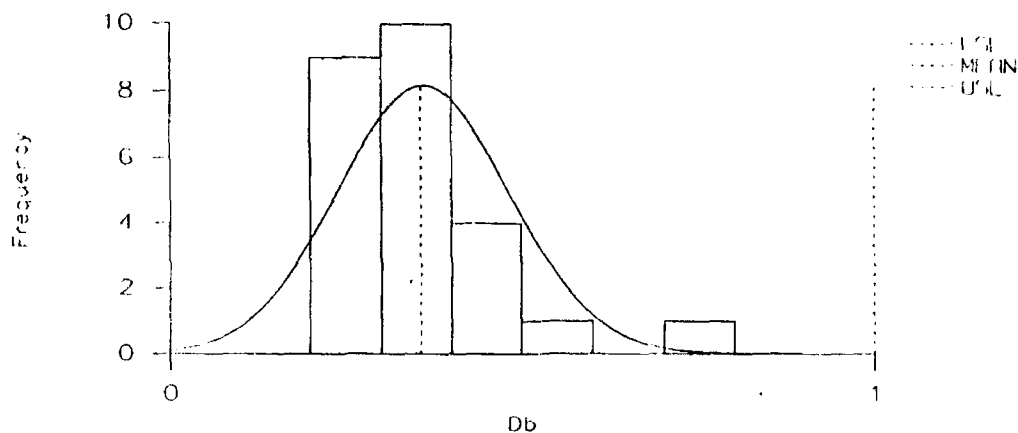
CAPABILITY INDEX (CPI) = 1.4058  
PROCESS INDEX (CPI) = 0.7113  
CPI INDEX (CPI) = 2.0609  
CPI INDEX (CPI) = 0.7511  
CPI INDEX (CPI) = 0.7511

ESTIMATED ACTUAL  
PRODUCT ABOVE SPEC = 0% 0%  
PRODUCT BELOW SPEC = 1.21% 0%  
TOTAL BEYOND SPEC = 1.21% 0%



UCL	0.004	CL = 0.267	UCL = 0.530
USL	0.000		USL = 1.000
subgroups	25	Control = 5.00 sigma	Rules = AT&T
Notes: Violated			
At 1 point above Zone A			

Figure 7-5. Loss at 25°C

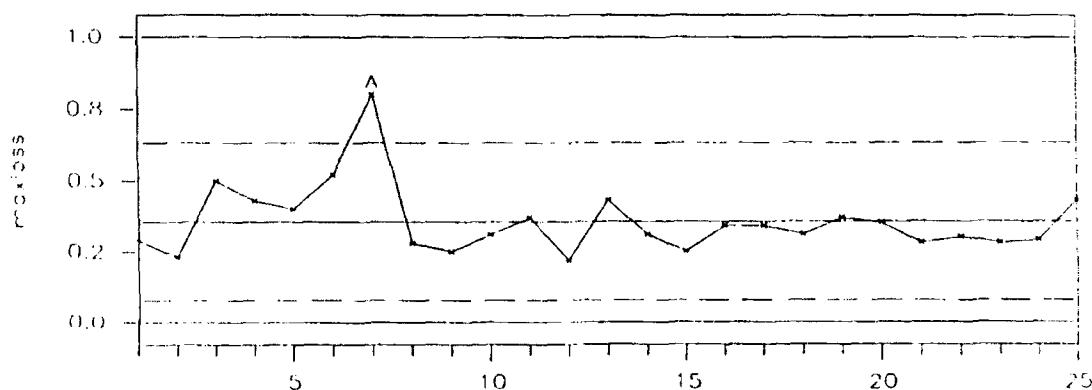


MEAN = 0.3552  
 STD DEV = 0.1219  
 +3.00 STD DEV = 0.7209  
 -3.00 STD DEV = -0.0106

MEAN LIMIT = 0.3552  
 SIGMA = 0.1219  
 UPPER SPEC LIMIT (USL) = 1  
 LOWER SPEC LIMIT (LSL) = 0

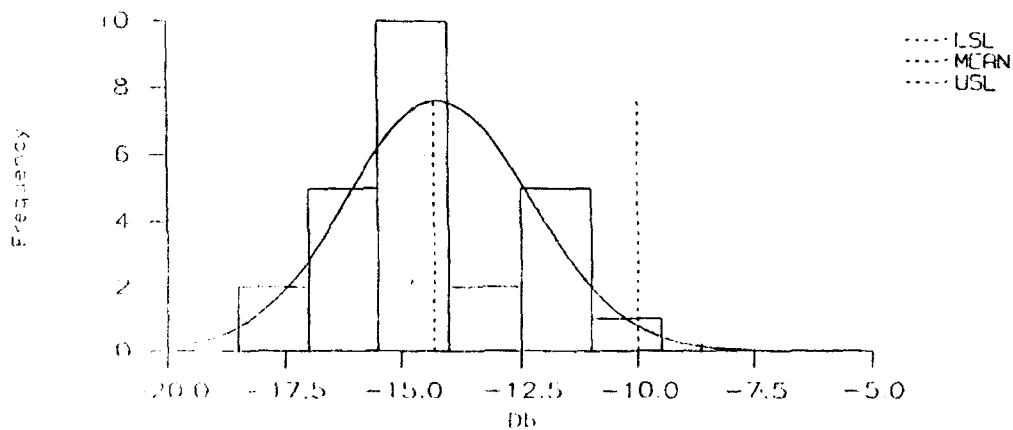
CAPABILITY INDEX (CP) = 1.3671  
 INVERSE INDEX (ICR) = 0.7315  
 UPPER INDEX (CPI) = 1.7631  
 LOWER INDEX (CPL) = 0.9711  
 CPK INDEX (CPK) = 0.9711

ESTIMATED ACTUAL  
 PRODUCT ABOVE SPEC = 0% 0%  
 PRODUCT BELOW SPEC = 0.18% 0%  
 TOTAL BEYOND SPEC = 0.18% 0%



--- LCL = 0.078	--- CL = 0.355	--- UCL = 0.637
--- LSL = 0.000		--- USL = 1.000
Subgroups : 25	Control : 3.00 sigma	Rules : AT&T
Rules Violated:		
A) 1 point above Zone A		

Figure 7-6. Maximum Loss (-55°C to 105°C)

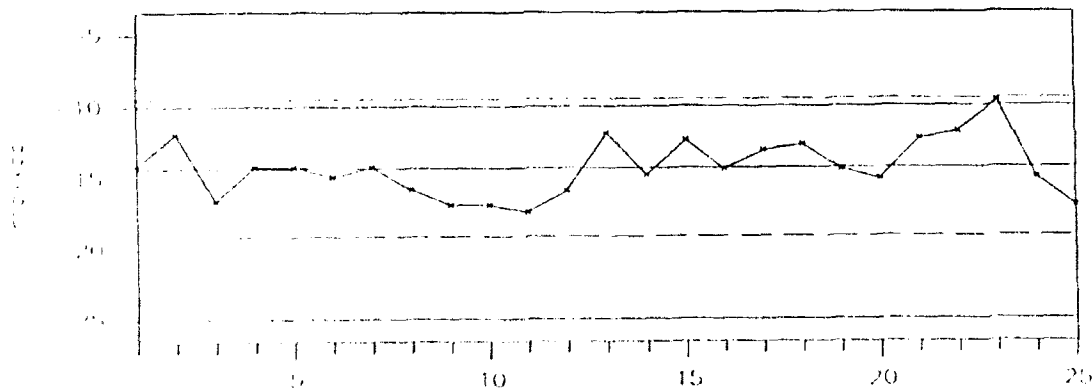


MEAN -14.304  
STD DEV 1.9673  
3.00 STD DEV -8.402  
6.00 STD DEV 20.206

MEAN LIMIT -14.304  
STDEV 1.9673  
UPPER SPEC LIMIT (USL) -10  
LOWER SPEC LIMIT (LSL) -25

CAPABILITY INDEX (CPI) = 1.2708  
CAPABILITY INDEX (CPI) = 0.7889  
UPPER INDEX (CPIU) = 0.7292  
LOWER INDEX (CPLI) = 1.8123  
CPIK INDEX (CPIK) = 0.7292

ESTIMATED ACTUAL  
PRODUCT ABOVE SPEC = 1.43% 4%  
PRODUCT BELOW SPEC = 0% 0%  
TOTAL BEYOND SPEC = 1.43% 4%



CL = -14.304	CL = -14.304	UCL = -9.484
LSL = -25.000		USL = -10.000
Subgroups = 25	Control : 3.00 sigma	Rules : AT&T
Rules Violated No violations detected		

Figure 7-7. Maximum Cross Coupling

## **SECTION 8**

### **LESSONS LEARNED**

Quadrupole wind, what is it and how is it done? In every presentation during the course of this program, it was readily apparent that if one did not thoroughly understand the basic mechanics of the Quadrupole wind itself, then it is virtually impossible to understand or comprehend the complexity of how to achieve it in an automatic, practically hands-free operation. Add to that the complexity of handling a delicate, small (100 to 250 microns), optical fiber and one has all the ingredients for an extremely difficult task. Such was the task of making an Automatic Coil Winding Station (ACWS). It was not only successfully done but achieved practically all of its goals.

Much of the credit for the success of the EMPI ACWS lies in Litton's 10 years experience in implementing similarly appropriate management and technical tools on other programs. For instance, TQM and concurrent engineering were heavily emphasized and wholly supported by management at all levels. Consequently, the transfer of the ACWS to the Salt Lake City production facility was smooth and the operators were already well versed on its function and ready to put it into production use.

Considerable credit must also be given to the Prototype Coil Winding Station in identifying the critical factor early in the program and during the initial design phases of the ACWS. Without its early availability, costs would have been substantially greater and the schedule would have been seriously impacted. It provided a lot of real hands-on experience with a copious amount of data that was readily extrapolated into the ACWS.

Moreover, it was the PCWS that made it abundantly clear that the key critical factor and control method for producing low-cost/high-yield FOG coils were fiber crossovers and fiber guide design, respectively. But ultimately, the final design had to be tested on the ACWS with its full robotics.

The TQM concepts cooperatively developed the QFD matrix after which one's focus remained on priorities despite temptation to deviate from these priorities while encountering numerous frustrations.

Like the QFD matrix, the Taguchi DOE methods also provided a valuable tool for identifying certain critical processes and weighing them accordingly to aid in facilitating a robust design. Without this approach, other process factors could have been easily but erroneously interpreted as the strongest factor in creating fiber crossovers.

Of course, initial SPC results, though limited to only 25 coils, are showing encouragingly significant results. Based on Litton's dedicated use of SPC on other programs, this effort will continue on

an on-going basis and provide the necessary in-sight for any program adjustment to both the coil design and/or the ACWS hardware/software.

Summarizing, consistent with TQM and concurrent engineering principles, the best lesson affirmed was the value of communications. Communications throughout the entire program were open with thorough documentation and dissemination of all material in a timely manner.

**APPENDIX A**

**OPTICAL PERFORMANCE TESTING  
AND PROCESS VARIANCE STUDY RESULTS**

## Optical Performance Testing

For the ACWS, the following optical performance goals or quality factors apply to coils wound on the PCWS and the ACWS.

- Polarization holding parameter (H-parameter)
  - Ability of coils to preserve state of polarization of launched light
$$H = \frac{\text{Power Cross-coupled to other polarization}}{\text{Launched Power} \times \text{Length}}$$
  - Low gyro bias temperature sensitivity requires low coil H-parameter
- Insertion Loss
  - Low insertion loss of the gyro optical components is required to obtain:
    - Reduced gyro angle random walk
    - Reduced electrical-crosstalk-induced bias error since the photodetector signal is larger
- Coil light transit time
  - Operation of the gyro at the proper frequency (half the inverse of the coil light transit time) is essential to eliminate many sources of bias error.
  - Proper frequency of different gyros (thus transit times of different coils) have to match to within 1 percent.

A study was done to identify the effect of crossovers on optical performance. In particular, insertion loss and H-parameter. Completed theoretical calculations indicated that crossovers do not affect gyro performance provided their quantity is approximately 1 percent or less of the total number of turns of fiber on the coils (200m coil).

For the study, three 200m coils were wound on the PCWS using the initial guides allowing crossovers to occur (2-10 per layer) without rewinding. Two additional coils were successfully wound using the new Rev 2 fiber guides and without any crossovers.

These experiments showed that the coils wound without crossovers exceed the LN-200 H-parameter specification when cycled from -55°C to +105°C.

As part of the machine compatibility study, tests were completed to verify that the PCWS could be used as a test bed for the design of the ACWS (see Table A-1).

**TABLE A-1. OPTICAL PERFORMANCE TEST DATA OF PROTOTYPE COIL WINDER STATION VS MANUAL WINDER STATION**

Parameter	LN-200 Specification (Normalized)	Prototype Winder*	Manual Winder*
Polarization Holding	<1.0	0.77	0.61
Insertion Loss	<1.0	0.95 $\pm$ 0.22	0.84 $\pm$ 0.46
Coil Transit Time	1.0 $\pm$ 0.01	1.04 $\pm$ 0.005	1.037 $\pm$ 0.014
Winding Time (hrs)	–	6	24
*Sample of 3 coils			

From the data, the optical performance test data of the PCWS is comparable to that of the manual winder station with one exception: the PCW coil winding time is one-fourth that of the manual winder station.

### Process Variance Study

The purpose of the process variance study, using the PCWS, was to identify the critical coil winding process factors that cause crossovers by exercising the controllable factors and verifying their effects with optical measurements.

The process variance study was based on the following constraints:

- Use a Taguchi L9 orthogonal array for experiments
- Conduct four repetitions per experiment
- Subject the output to cross-sectional analysis for test results
- Target coil geometries (e.g., fiber gap)
- Minimum variance of geometry from coil to coil
- Minimum variance of geometry within each coil.

For the L9 array, the controllable or main factors are the following:

Main Factor	Units	Range
Fiber gap (space between turns)	micron	20, 40, 60
Guide position	—	Inside, outside
Speed	rpm	Way out
Tension	grams	50, 100, 150 3, 10, 20

Baseline Factors:

- Use the PCWS
- Aluminum spools for the coils
- PM fiber
- Quadrupole wind

The following L9 experiments were set up and performed:

- One fiber-layer wind on aluminum spool
- One fiber-layer wind on first fiber layer
- One fiber-layer wind on aluminum spool with fiber guides grounded and air ionizer installed (to eliminate any effects of electrostatic charge on causing crossovers).

Refer to Figures A-1, A-2, and A-3 for the aforementioned matrices and crossover data. The crossover averages and the main factors averages for each experiment are summarized in conventional form and presented in Table A-2.

**TABLE A-2. CROSSOVER AND MAIN FACTOR AVERAGES**

Experiment	Average No. of Crossovers/Layer	Strong Effect	Recommended Value
Fiber on Aluminum	5	Fiber Gap	40 $\mu\text{m}$
Fiber on Fiber	15	Fiber Gap	60 $\mu\text{m}$
Fiber on Aluminum with grounding and air ionizer	2	Fiber Gap	40 or 60 $\mu\text{m}$

I.9 (3-4) Array				
#	A	B	C	D
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

Main Factors				
Fiber Gap	Gde.Pos.	Speed	Tension	
20	Inside	50	lowest	
20	Outside	100	10	
20	Way Out	150	20	
40	Inside	100	20	
40	Outside	150	lowest	
40	Way Out	50	10	
60	Inside	150	10	
60	Outside	50	20	
60	Way Out	100	lowest	

# CROSSEOVERS

Spool A-1		Spool B-1		Avg.	STD	Total
Run#1	Run#2	Run#1	Run#2			
41	39	0	2	20.5	22.55	82
29	34	9	0	18	16.15	72
9	4	0	0	3.25	4.272	13
2	0	0	0	0.5	1	2
0	4	0	0	1	2	4
0	0	0	0	0	0	0
0	0	7	3	2.5	3.317	10
0	0	0	0	0	0	0
0	0	0	0	0	0	0

Avg. = 9	Avg. = 1.167	Avg. = 5.083	183
STD = 15.06	STD = 2.64	STD = 11.38	

## Averages

Response Table w.r.t. # of Crossovers			
Fiber Gap	Gde.Pos.	Speed	Tension
13.9	7.8	6.8	7.2
0.5	6.3	6.2	6.8
0.8	1.1	2.3	1.3
13.4	6.7	4.5	5.9

Level	
1	
2	
3	
Difference	

Strong Effect	Paper Champ
Fiber Gap	A 2
	B 3
	C 3
	D 3

Figure A-1. EMPI Coil Wind Experiment—One-Layer Wind (90° Turns) on Aluminum Mandrel

# CROSSOVERS

L9 (3-4) Array					Main Factors				Spool A-1		Spool B-1		Avg.	STD	Total
#	A	B	C	D	Fiber Gap	Gde.Pos.	Speed	Tension	Run#1	Run#2	Run#1	Run#2			
1	1	1	1	1	20	Inside	50	lowest	33	39	37	33	35.5	3	142
2	1	2	2	2	20	Outside	100	10	22	22	7	10	15.25	7.89	61
3	1	3	3	3	20	Way Out	150	20	18	23	15	18	18.5	3.317	74
4	2	1	2	3	40	Inside	100	20	16	16	18	17	16.75	0.957	67
5	2	2	3	1	40	Outside	150	lowest	23	19	23	22	21.75	1.893	87
6	2	3	1	2	40	Way Out	50	10	21	17	22	20	20	2.16	80
7	3	1	3	2	60	Inside	150	10	3	5	6	4	4.5	1.291	18
8	3	2	1	3	60	Outside	50	20	0	0	1	0	0.25	0.5	1
9	3	3	2	1	60	Way Out	100	lowest	0	0	0	3	0.75	1.5	3

A-6

Avg. = 15.39	Avg. = 14.22	Avg. = 14.81
STD = 11.72	STD = 11.08	STD = 11.26

533

## Averages

Response Table w.r.t. # of Crossovers			
Fiber Gap	Gde.Pos.	Speed	Tension
23.1	18.9	18.6	19.3
19.5	12.4	10.9	13.3
1.8	13.1	14.9	11.8
21.3	6.5	7.7	7.5

Strong Effect		Paper Champ	
Fiber Gap	A	3	
	B	2	
	C	2	
	D	3	

Figure A-2. EMPI Coll Wind Experiment—One-Layer Wind on Dry Fiber Layer

L9(3 <sup>4</sup> ) Array					Main Factors				Spool A-1		CROSSEVERS		
#	A	B	C	D	Fiber Gap	Gde. Pos.	Speed	Tension	Run#1	Run#2	Avg.	STD	Total
1	1	1	1	1	20	Inside	50	lowest	14	8	11	4.243	22
2	1	2	2	2	20	Outside	100	10	0	2	1	1.414	2
3	1	3	3	3	20	Way Out	150	20	2	1	1.5	0.707	3
4	2	1	2	3	40	Inside	100	20	0	0	0	0	0
5	2	2	3	1	40	Outside	150	lowest	0	0	0	0	0
6	2	3	1	2	40	Way Out	50	10	0	0	0	0	0
7	3	1	3	2	60	Inside	150	10	0	0	0	0	0
8	3	2	1	3	60	Outside	50	20	0	0	0	0	0
9	3	3	2	1	60	Way Out	100	lowest	0	0	0	0	0
									Avg. = 1.5		Avg. = 1.5		27
									STD = 3.666		STD = 3.666		
Averages					Response Table w.r.t. # of Crossovers				Strong Effect		Paper Champ		
Level	Fiber Gap	Gde. Pos.	Speed	Tension	Fiber Gap	A	3						
1	4.5	3.7	3.7	3.7		B	2						
2	0	0.3	0.3	0.3		C	2						
3	0	0.5	0.5	0.5		D	2						
Difference	4.5	3.4	3.4	3.4									

**Figure A-3. Fiber Guides Grounded and Air Ionizer Installed**

From the above summary and the previous studies, the following conclusions were established:

- Fiber crossovers are a key design issue
- Fiber gap is a process factor critical to fiber crossovers and variation in the fiber gap is a primary cause of crossovers.
- A large fiber gap, i.e., 60  $\mu$ m, compensates for gap variation and reduces crossovers
- The fiber guide is a factor critical for fiber gap uniformity, subsequently reducing crossovers
- The fiber-on-fiber data indicated that the quality of the underlying surface, i.e., fiber layer, causes crossovers. As a result, the coil geometry is a critical design factor.
- Reducing crossovers by grounding the fiber guides and installing an air ionizer was inconclusive and was not further investigated.
- The fiber itself can be a significant noise source.

A 20-layer confirmation coil was wound using the following critical process factors:

Gap	60 $\mu$ m
Guide Position	Wayout
Winding Speed	100 rpm
Winding Tension	3 grams
Number of layers	20

The first 12 layers were successfully wound without crossovers. However, layers 13–20 had crossovers. This is a manufacturing concern because it is apparent that once crossovers start, they then tend to accumulate due to the quantity of the fiber layers.

With the fiber gap now firmly identified as the primary critical process factor (primary cause of crossovers), work was directed toward fiber gap variation control methods. From the Taguchi data it was concluded that the fiber guide was the main control method to address.

## **APPENDIX B**

### **FIBER CROSSOVERS AND POTENTIAL CAUSES**

When manually winding fiber on sensor coils, fiber crossovers are always a problem. To remove them, the operator would unwind and then rewind to remove the crossover and then continue with the wind. A discussion of crossovers and what causes them is presented.

A fiber crossover is defined when a fiber turn on the coil is wound on top of, instead of adjacent to, the previous turn. Large unpredictable variations in the fiber gap, the space between adjacent turns, cause the fiber to lead the fiber guide on the manual winder rather than lag the guide. With a large enough leading angle, the force acting on the fiber during winding is sufficient to cause the fiber turn to lie on top of the previous turn rather than adjacent to it.

Possible causes of fiber crossover, resulting from studies on the EMPI program are listed below:

- |                                                 |                                                                                              |
|-------------------------------------------------|----------------------------------------------------------------------------------------------|
| • Variations in fiber diameter and fiber Memory | – Treated as noise                                                                           |
| • Nonuniformity of previous layer               | – Treated as noise                                                                           |
| • Static charge on the spool                    | – Experiments show experiment with grounding and air ionizer                                 |
| • Static charge on the fiber                    | – Previous preliminary experiments show no effect                                            |
| • Tension variation (spikes)                    | – Previous experiments show small tension spikes have no effect                              |
| • Motion control errors                         | – Preliminary analysis indicates negligible effect due to variation in fiber guide movements |
| • Particles on fiber or spool                   | – Fiber storage improved and an air ionizer installed                                        |
| • Fiber guide                                   | – Fiber leading the fiber guide                                                              |

## **APPENDIX C**

### **PAYGUIDE ASSEMBLY AND FIBER GUIDE DESIGN REVISIONS**

Provided herein are photos and drawings of the fiber payguide assembly (PGA). Figure C-1 shows the entire station: electronics console, computer keyboard and monitor and part of the motion controller where the payguide assembly is located. Figure C-2 is a closer view of the motion controller. Subsequent photos, Figure C-3 through Figure C-7 are self explanatory views, by their respective titles, of the payguide assembly and supporting details.

As seen from both the photos and drawing illustrations, the PGA is a complicated mechanism attached to a robotic manipulator. As stated earlier, ref Appendix A, a thorough understanding of quadrupole winding is essential to understand the full workings of the ACWS. While the payguide function is basically quite simple, the detail problems connected with it are not. The fiber is

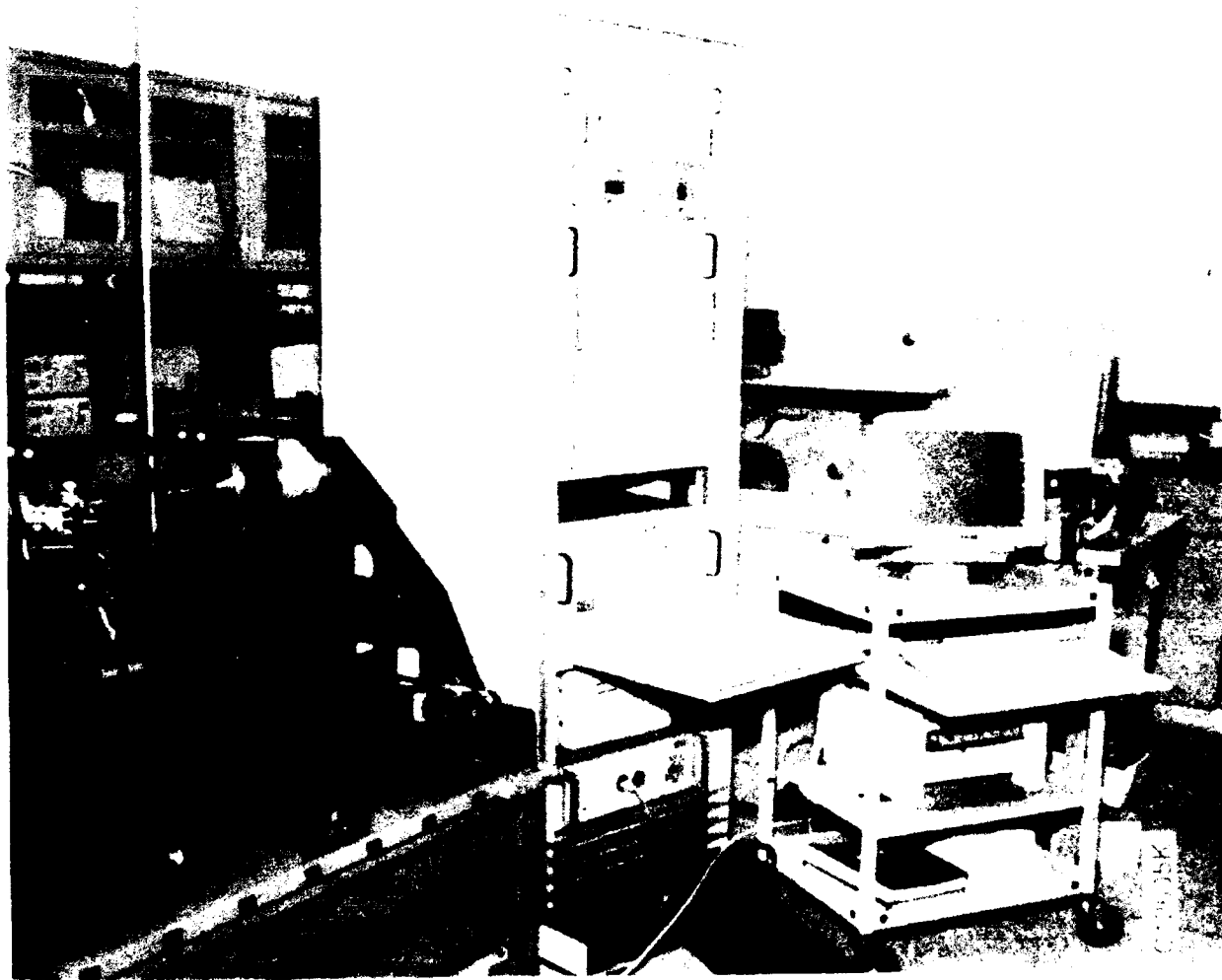
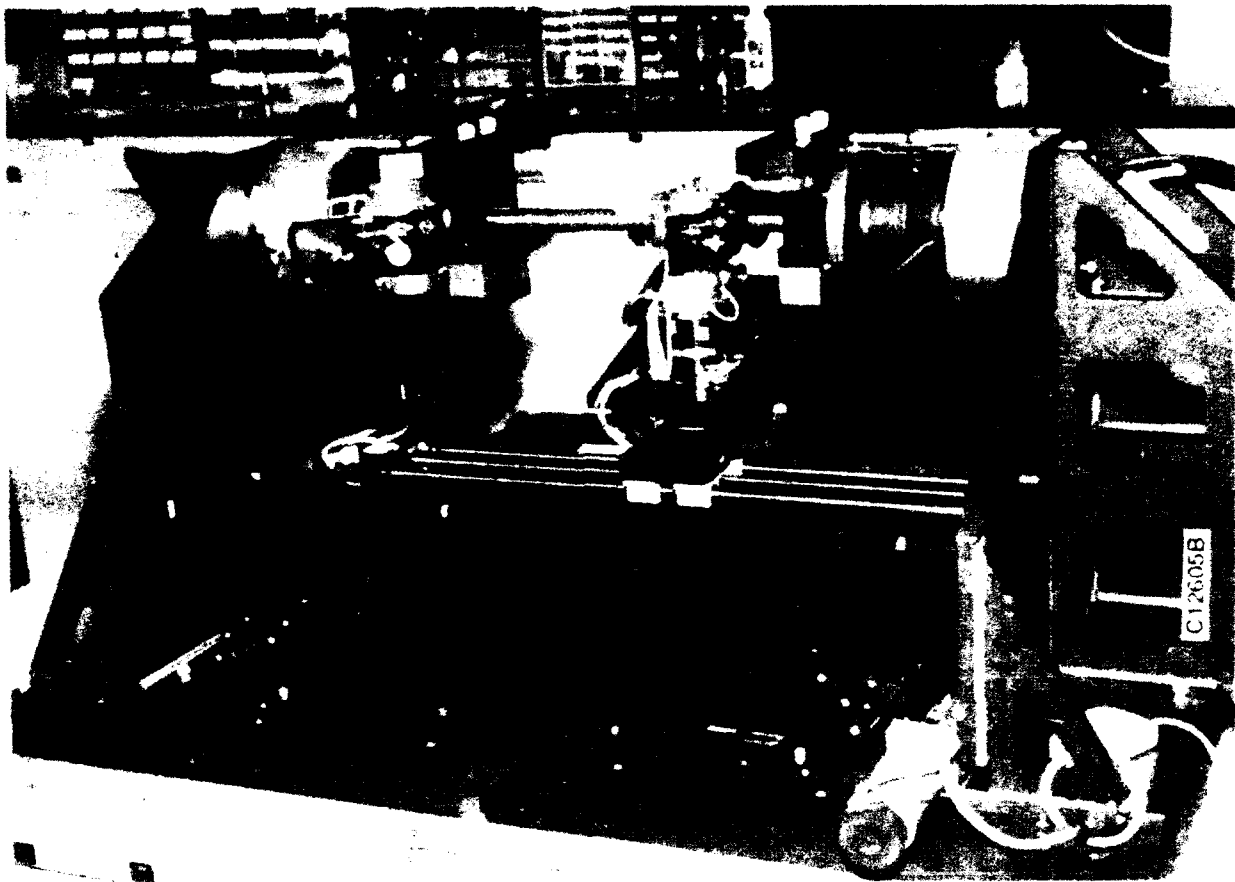


Figure C-1. ACWS Electronics Bay



**Figure C-2. ACWS Motion Control Subsystem**

delicate, crossovers must be avoided, fiber tension must be maintained low while at the same time being held under control, and finally, speed is essential to achieving payback on the investment. As a result, the PGA presented numerous problems with each iteration providing some relief to the problems encountered earlier. The most significant modifications occurred in the fiber guide mechanism which eventually had to go through four major iterations. A discussion of each follows.

- a. Baseline payguide – This guide, Figure C-8, was the first design; thus, the name baseline. The trough (groove) where the fiber traveled was actually made from a hypodermic needle axially split (Item 43), and attached to the main support member, Item 32. In use, the trough was not deep enough to keep the fiber from jumping out. On the other hand, a deeper trough would not have permitted fiber guide right up to the point of tangency of fiber contact to the spool arbor. Additionally, the design caused a large flange/coil gap. The poor gap control would have led to many crossovers had the fiber been retained.



**Figure C-3. ACWS Paygulde Assembly Coupled to Holding Bracket**

- b. Revision 1 – This design, Figures C-9 and C-10, was conceived to overcome the deficiencies of the baseline design by holding and guiding the fiber right up to the point of tangency to the spool arbor. To facilitate that objective, a cutout was made immediately behind the guide to allow clearance above the arbor. Beyond that, the support arm was made beefier to provide greater rigidity to the support. Again, like the baseline design, it would not retain the fiber captive in the trough. Nonetheless, it exhibited considerable improvement in the geometric quality as opposed to the baseline design. Later, a stiffener bar was added to the upper section of the support arm to provide even more rigidity. All of this provided some, but not enough, improvement in the fiber/flange gap but not in fiber retention. Another approach was necessary.

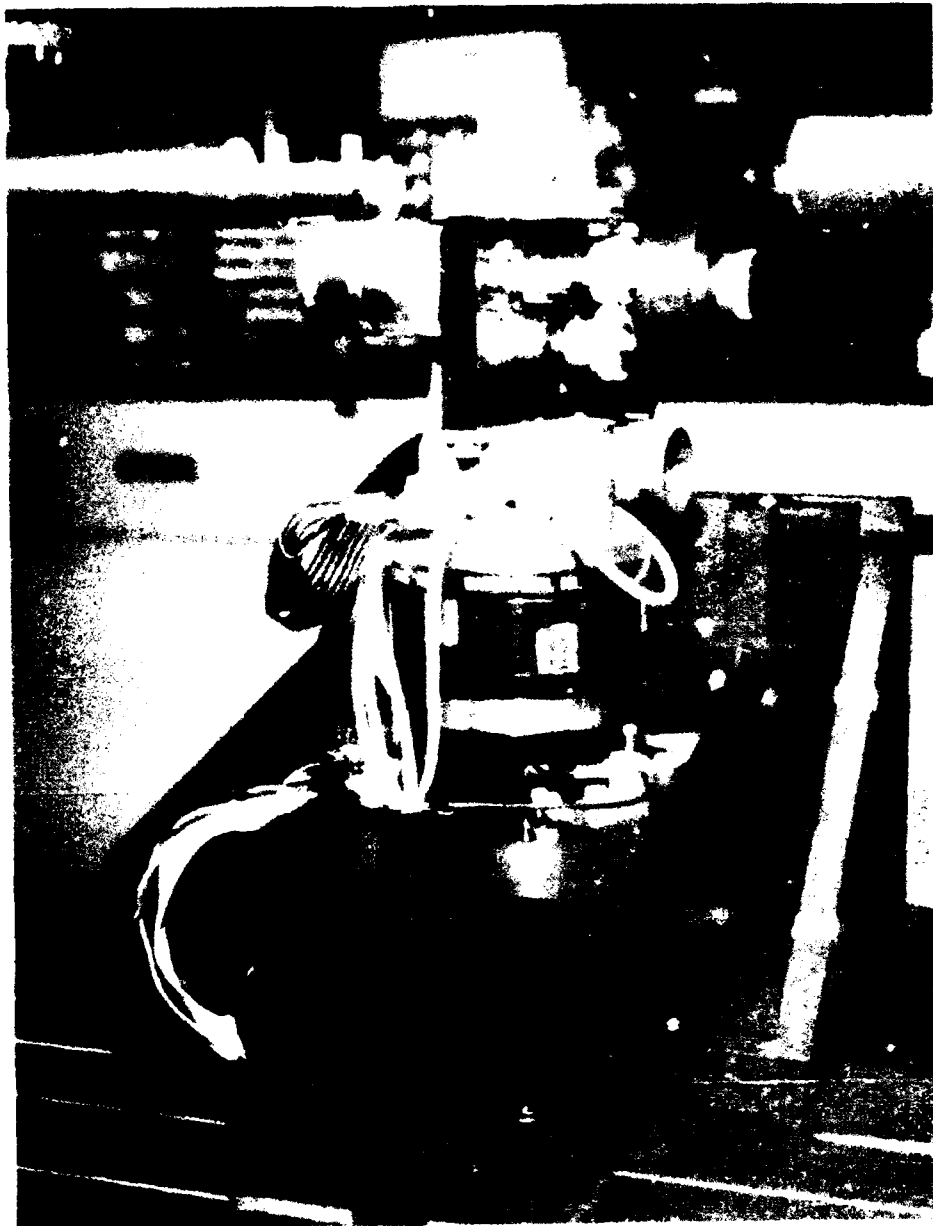
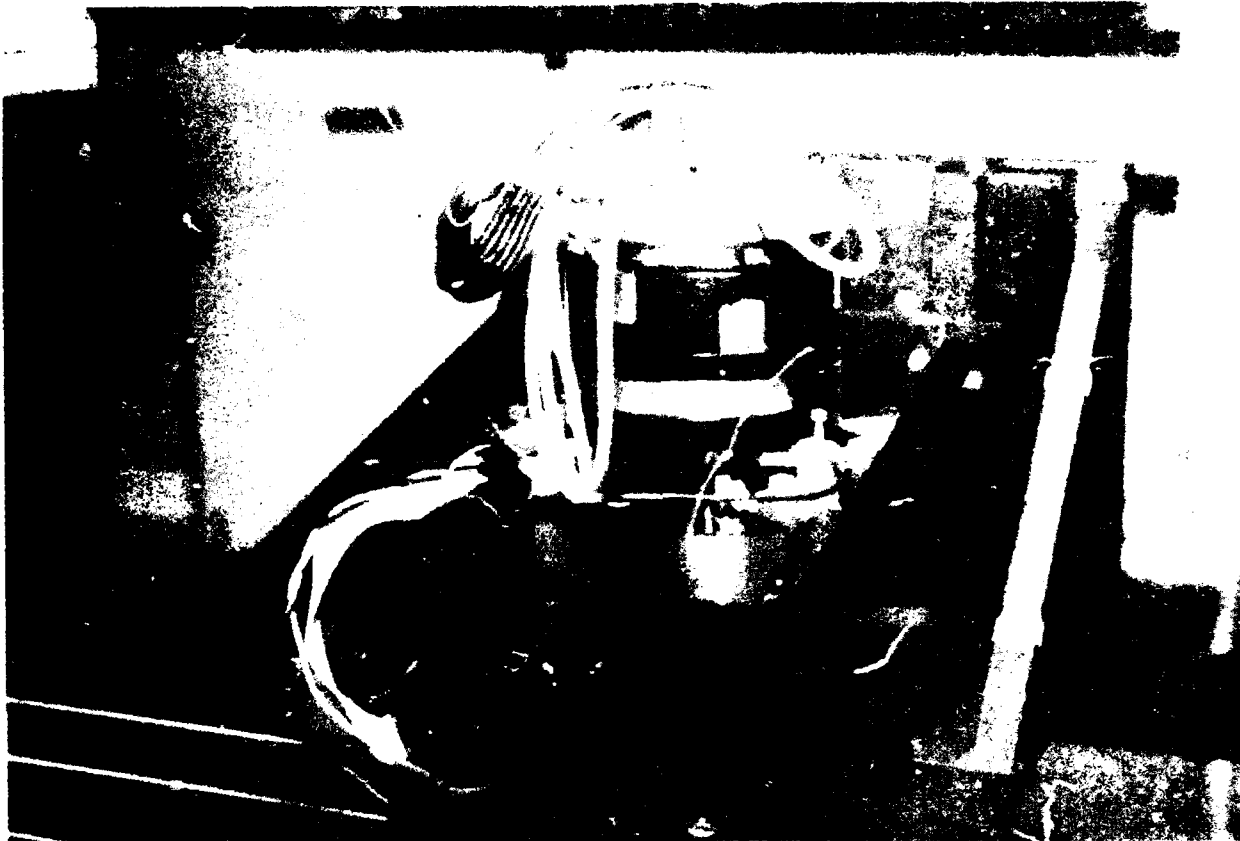
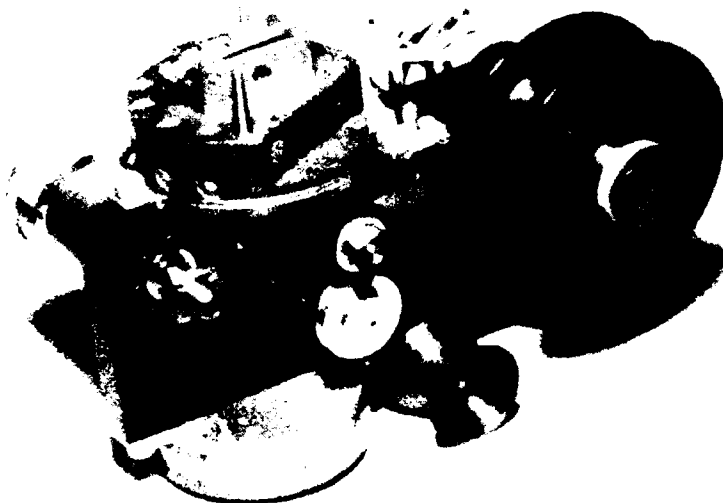


Figure C-4. Robotic Manipulator Holding Payguide Assembly



**Figure C-5. Robotic Manipulator without Payguide Assembly**

- c. Revision 2 – Figure C-11 shows that this revision again tried to capitalize upon what was learned from the earlier designs. It was to provide sturdier, amply thicker, support of the guide as close to the point of fiber tangency to the spool arbor as possible. The fiber groove was much deeper to retain the fiber, but to prevent damage to fiber already laid down, an arc section with an approximate profile of the arbor at the point of tangency was cut away. Again, at the point of fiber payout or tangency to the arbor, the fiber guide was kept as thin as possible for gap control. These added features showed more promise, because now it was possible to run many turns on the spool, something that had not been accomplished earlier. That accomplishment, however, surfaced a new problem: Abrasion to the fiber jacket.



C12605E

**Figure C-6. Payguide Assembly (Front View)**

Abrasion was in actuality probably not a brand new problem. It's just that with so little winding being accomplished, very little attention had been given to abrasion. Cause of abrasion was further exacerbated by the fact that the vendor made a change in the jacket material. With no older fiber available to assess the true cause, it was decided that an entirely different approach was necessary in the event that the new jacket material proved better for optical reasons. Thus, a whole new concept was explored.

- d. Revision 3 – Figure C-12 approach consisted of a rotary wheel guide to eliminate any sliding effect of the fiber against an adjacent surface. Additionally, as the illustration shows, a second wheel, later removed, was to run against the larger guide wheel to help retain the fiber in the guide groove. Figure C-13 shows a photograph of the Revision 3 guide mounted to the ACWS payguide assembly.



**Figure C-7. Paygulde Assembly (Rear View)**

As promising as the Revision 3 this approach seemed, it also wasn't without some problems. Wheel flatness proved to be a problem because of its thin wafer profile. Therefore, the material had to be changed. Once the flatness was resolved, then there was a runout problem caused by the bearing – a bushing. To minimize wheel wobble, the bushing clearance had to be very minimal. However, because of this there would occasionally be some binding which would feed back up through the fiber and into the tension controller creating other problems. This was eventually changed to a ball bearing. After resolving these two problems, it was then possible to even remove the smaller captivating wheel altogether. Finally, the fiber guide and payout guide assembly seemed to meet its objectives: no abrasion to fiber jacket and gap control was sufficient to prevent crossovers. With the payout guide assembly now controllable, the rest of the control must come from the operator through software control.

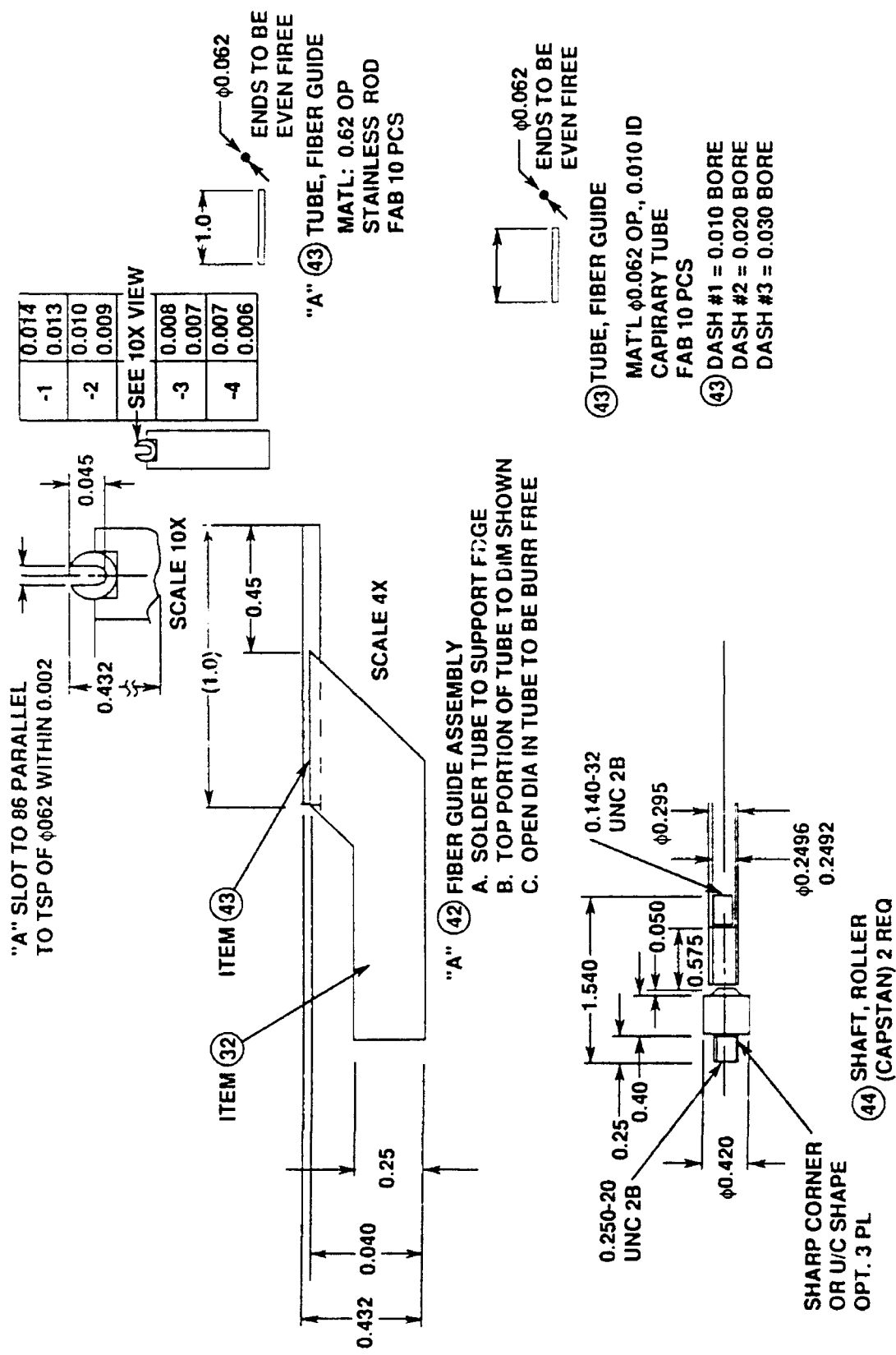
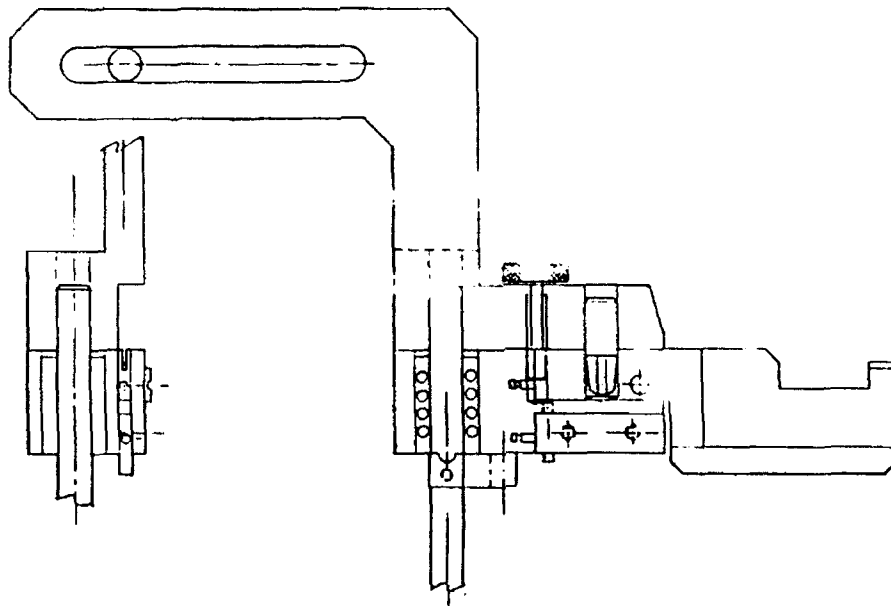
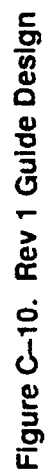


Figure C-8. Prototype Station Baseline Guide Design



**Figure C-9. Guide Redesign**

For best control results, each layer must have a smooth profile. A crossover allowed to develop in one layer can exacerbate chances of having a good profile on the next and subsequent layers. The operator will play a significant role in achieving this since it is heavily dependent upon controlling fiber gap. Therefore, the operator must carefully choose the proper software gap setting. Additionally, the wheel groove must be kept clean and monitored against any wear that could introduce wheel wobble. Meanwhile, additional fine tuning variability reduction exercises may prove necessary to further optimize the gap setting and to control fiber crossovers.





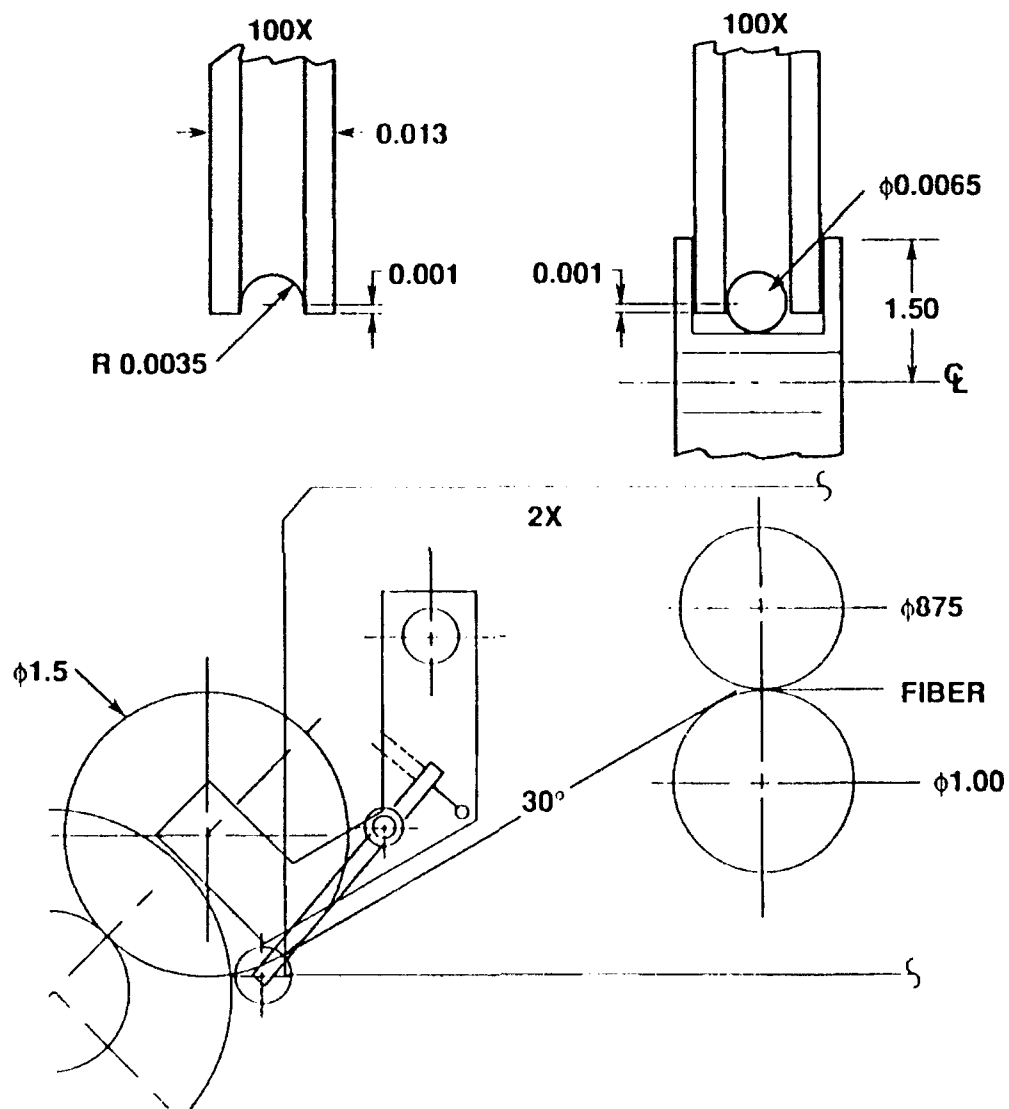
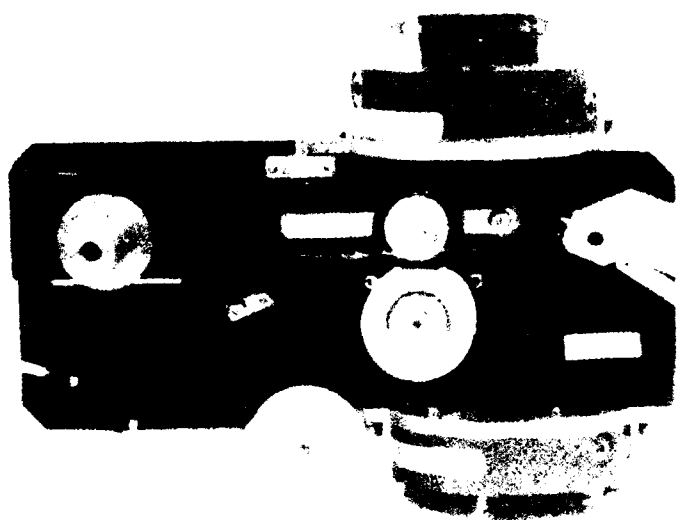


Figure C-12. Rev 3 Gulde Design



**Figure C-13. ACWS Paygulde Assembly and Rev 3 Fiber Guide**